

**Exploration of differences in vertical jump performance between
typically developing children and those identified with DCD: A
kinematic and kinetic analysis.**

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Statement of Sources

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ABSTRACT

This study compared the motor performance of children identified with Developmental Coordination Disorder (DCD) with those of a matched group categorised as typically developing (TD). Based on the existing literature, vertical jumping was the task selected as it is a fundamental movement skill (Gallahue & Ozmun, 2002), and a single optimal coordination pattern has been shown to exist (e.g., Bobbert & van Ingen Schenau, 1998). Within the conceptual framework developed for this enquiry, jump height, the performance outcome, was the highest level variable. Level 2 variables described the centre of mass displacement at key instants during the jumping movement. Level 3 variables identified measures of velocity, force and power, which underpin the movement, and level 4 variables described the countermovement specific to this task. This provided a more thorough analysis than previously reported in DCD literature for jumping. The objective of this study was to identify possible mechanisms of DCD in order to advance the understanding of this impairment.

A cross-sectional sample (n = 165) of males and females aged between 5 and 12 years was drawn from a school in Victoria, Australia. Using the Movement–Assessment Battery for Children (M-ABC), 62 children from the sample were identified as having DCD with total impairment scores below the 15th percentile for their age-band (Henderson & Sugden, 1992). From the remaining children assessed, who all scored above the 15th percentile, 62 were matched with the DCD group to form the TD group (n = 62). Participants performed three maximal vertical jumps, standing on a single

forceplate. Each child's best vertical jump was analysed using forceplate (700 Hz) and 2D sagittal kinematic data from a single camera video (50 Hz) capture.

The results confirmed previous findings that DCD children jump lower than their TD peers, although there was a considerable overlap in motor ability between the groups. Peak VCOM occurred earlier in the jumping movement in the DCD group, when compared to the TD group. This meant a longer elapsed time from the instant of peak VCOM to take-off, which was attributed to coordination error. The earlier occurrence of peak VCOM in the DCD group could be explained by the lower shank angular velocity at take-off. In addition, the DCD group produced lower jump impulse and peak power.

Further probing of the jump height data revealed an interesting relationship between age-band and jump height that was gender specific. It was noted that for the DCD males, less than 1% of the variance found in jump height could be accounted for by age-band. In contrast, the explained variance for jump height by age-band was 24% for the TD males. The females showed similar relationships for jump height and age-band in both groups. It was thought that this may reflect physical activity avoidance caused by greater social pressures on boys to be good at sports (e.g., Parker & Larkin, 2003).

In addition, a further analysis of the DCD group data was undertaken to compare those who had difficulties in dynamic balance and those who did not. In this analysis, body mass was found to have a significant effect on leg stiffness (K_{leg}), and when accounted for as a covariate, greater K_{leg} in the DCD group with dynamic balance difficulties was found. A possible explanation is that for the DCD group with dynamic balance

difficulties, the transition from joint flexion to extension during the countermovement was problematic, and resulted in excessive muscle co-activation.

This study provides some possible directions for further investigations into coordination issues for DCD children. The time elapsed from peak VCOM to take-off and the shank angular velocities at take-off were identified as key indicators of a poorly coordinated jump. High levels of K_{leg} reflected difficulties in the transition from joint flexion to extension during the countermovement in those DCD children with dynamic balance problems. Based on these key variables and others that differentiated between groups a more parsimonious conceptual framework is presented.

For future enquiry, a more holistic approach for the study of children with such impairments is recommended. This includes exploring the environment these children are exposed to in order to gain a more thorough understanding of practice and learning effects. Understanding of differences in motor ability requires an expanded framework to include information on genetic and socio-cultural factors, and their impact upon important psychology, physical fitness, nutrition, body composition and physical activity parameters.

CHAPTER I

INTRODUCTION

There are children who have significant difficulties in coordinating movement, but show no physical or ‘hard’ signs of neurological impairment. These children are often intellectually able, yet have difficulty in acquiring movement skills (Barnett, Kooistra & Henderson, 1998). As early as 1937, these children were recognised as ‘clumsy’, a classification which carried an undesirable stigma (Coleman, Piek & Livesey, 2001).

The term “Developmental Coordination Disorder” (DCD) was introduced by the American Psychiatric Association (APA) in 1987, yet the term DCD did not consistently appear in literature until 1992 (Geuze, Jongmans, Schoemaker & Smits-Engelsman, 2001). Since 1987, a refined definition of DCD was introduced (APA, 1994). There is now some consensus amongst researchers and clinicians that this concept of DCD should be used whenever research or clinical observations are published (Missiuna, 2001) and it has become a common label for children who have difficulties in motor proficiency (Geuze et al., 2001).

Worldwide, between five and ten percent of children are believed to have DCD (APA, 2000; Gubbay, 1975; Henderson & Hall, 1982; Kadesjo & Gillberg, 1999; Keogh, 1968; Larkin & Rose, 1999; Sovik & Maeland, 1986). It has been estimated, however, that only a fraction of cases will be identified due to financial constraints, time requirements for screening and the lack of a concise descriptor (Hay, Hawes & Fraught, 2004).

Furthermore, there is no gold standard for the assessment of motor impairment in children. As such, there are many issues relating to the assessment of motor impairment that remain unresolved (Henderson & Barnett, 1998).

Over forty-five movement assessment batteries exist to assess children's movement skills with each testing different areas of motor performance (Burton & Miller, 1998). One clinically recognised test is the Movement Assessment Battery for Children (M-ABC; Henderson & Sugden, 1992). The recent popularity of the M-ABC for testing the presence of movement disorders in children is well documented (e.g., Smyth & Mason, 1997).

Characteristics of DCD are broad and associated with problems in “almost any sensory or motor skill imaginable” (Visser, 2003, p 480). For some, DCD is a relatively generalised problem, affecting movement, as well as perception. Yet for others, difficulties are very specific, showing that subgroups exist within the DCD population (Visser, 2003). This means that some DCD children may perform at the same level as the general population on a particular measure (Wright & Sugden, 1996), but not on others.

Generally, daily activities provide children with the necessary stimulus for motor learning. The basic process of physically interacting with the environment provides the nervous system with information to modify how it controls movement. Children refine their muscular activation patterns through various movement experiences and interactions with the environment (Basmajian & De Luca, 1985). From the outset, childhood ‘play’ involves performance of fundamental movements such as running, walking, skipping,

climbing, hanging and rolling (Hands & Larkin, 2002). 'Play' is therefore important to children because it provides movement experiences and the stimulus to develop both physical competence and fitness.

Children identified with DCD often avoid physical activity and lead sedentary lives. The consequences of this avoidance may include not only inefficient muscle activation patterns (Bouffard, Watkinson, Thompson, Causgrove Dunn & Romanow, 1996), but also socio-emotional consequences such as depression and social isolation (Bar-Or & Rowland, 2004; Rasmussen & Gillberg, 2000). Over time, the avoidance or withdrawal from physical activity or hobbies may also lead to a reduction in physical fitness (Parker & Larkin, 2003) and increased levels of obesity (Dewey & Wilson, 2001). Generally, DCD children score below the minimal standard when assessed by the Australian Schools Fitness Standards (Pyke, 1986). Children identified with DCD have been found to be significantly heavier (Visser, Geuze & Kalverboer, 1998) and to have a higher Quetelet index (mass/stature). Thus, long term withdrawal from physical activity appears related to a decline in health status, which is a particular concern.

Jumping for height is an integral part of play, and therefore, one of the fundamental movement skills for children (Gallahue & Ozmun, 2002). Typical motor development generally follows a logical sequence. Walking and running, for example, are generally followed by double foot propulsion or the ability to jump off a supporting surface. By the age of two years children begin to jump. However, it is not until the age of three or four years that a well coordinated effort is consistently seen (Clark, Phillips & Petersen, 1989;

Jensen, Phillips & Clark, 1994; Phillips, Clark & Petersen, 1985). The recognisable 'mature' pattern of jumping is usually evident by the age of six years (Gallahue & Ozmun, 2002), which, coincides with noticeable strength gains (Malina, Bouchard & Bar-Or, 2004). The strength gains are required to propel the body off the ground (Gabbard, 1992), as well as for posture and control of balance.

In typically developing (TD) children, jump performance progresses with age. Detectable improvements in jump height have been reported from four to 30 years of age (Bosco & Komi, 1980). To date, vertical jump performance comparisons between TD children and those identified with DCD have not been comprehensively studied. In general, the DCD research involving jumping has been limited to discrete measures such as jump height and qualitative descriptions (Hammond & Dickson, 1994; Larkin & Hoare, 1991).

Investigators have proposed that for jumping, one optimal coordination pattern exists, which provides the most favourable conditions for performance (Bobbert & van Ingen Schenau, 1988; Hatze, 1998; Vanrenterghem, Lees, Lenoir, Aerts & DeClercq, 2004). The coordination of jumping found in TD children, therefore, potentially offers a useful framework for a more general study of coordination in DCD children. Group differences in selected dependent variables may therefore provide an insight into the identification of possible mechanisms underpinning DCD. This study will involve a comprehensive analysis of vertical jumping using a full range of kinematic and kinetic data, which has not previously been reported.

The following literature review is presented in three sections. The first chapter reviews the literature on how DCD is described, the prevalence of DCD, how DCD children have been identified, the effects of DCD, and the long term concerns. In chapter three, the movement pattern of jumping is reviewed and in chapter four the potential of the vertical jump to quantify differences between TD children and those identified with DCD is analysed.

CHAPTER II

LITERATURE REVIEW

PART I: DEVELOPMENTAL COORDINATION DISORDER (DCD)

2.1. Description and Overview of DCD

Research has advanced our understanding of motor impairment by showing that it is not simply a transitional difficulty or delay in development (Geuze & Börger, 1993; Losse, Henderson, Elliman, Hall, Knight & Jongmans, 1991). Rather, findings support an identifiable disorder of movement skill capability, requiring aetiological, diagnostic and remedial attention in its own right (Henderson & Barnett, 1998).

A detailed historical overview of the broader context of motor impairment has been presented by Rispen and van Yperen (1998) under the unifying umbrella of specific developmental disorders. These disorders include problems with learning, language, speech and movement. Over time, the classification of various disorders has become highly structured and specific. Since Rispen and van Yperen's overview, the literature has highlighted the difficulties in identifying motor impairment in a developing child (e.g., Geuze et al., 2001; Missiuna, 2001; Visser, 2003). A summary, of the descriptive terms traditionally used to categorise children with motor impairment is presented in Table 2.1. It shows a number of descriptors of motor impairment. 'Clumsy' has been the most frequent term used since 1937 (Orton, 1937). Less frequently used descriptors have included 'apraxia', 'developmental apraxia', 'developmental dyspraxia', 'dyspraxia',

‘dysgnosia’, ‘delayed movement difficulties’ and ‘minimal brain dysfunction’(Henderson & Barnett, 1998).

Table 2.1: Examples of descriptors of motor impairment conditions (adapted from Henderson & Barnett, 1998)

Term	Author(s)
Clumsy, developmental clumsiness	Orton (1937) British Medical Journal (1962) Walton, Ellis and Court (1962) Gubbay, Ellis, Walton and Court (1965) Gordon (1969) Dare and Gordon (1970) Gubbay (1975) McKinlay (1978) Keogh, Sugden, Reynard and Calkins (1979) Henderson and Hall (1982) Hulme, Biggerstaff, Moran and Mckinlay (1982) Knuckey and Gubbay (1983) Hulme and Lord (1986) van Dellen and Geuze (1988)
Apraxia, developmental apraxia, developmental dyspraxia, dyspraxia - dysgnosia	Orton (1937) Walton et al. (1962) Gubbay (1978) Lesny (1980) Denckla (1984) Cermak (1985)
Physically awkward	Wall (1982) Wall , Read and Paton. (1990)
Poorly coordinated	Johnston, Short and Crawford (1987)
Motor infantilism	Anell (1949)
Delayed motor development	Illingworth (1968)
Children with movement difficulties	Henderson, May and Umney (1989) Sugden and Keogh (1990)
Minimal brain damage	Forsstrom and von Hofsten (1982)
Minor neurological dysfunction	Schellekens, Scholten & Kalverboer (1983) Touwen (1993)
Perceptuo-motor dysfunction	Laszlo, Bairstow, Bartrip and Rolfe (1988)

This use of a number of terms to describe motor impairment was noted further by Geuze et al. in 2001. They reviewed 164 publications from 1989 to 1999 and 12 pioneering studies prior to 1989. Geuze et al. found the term ‘clumsy’ or ‘clumsiness’ to be the most frequent descriptor of motor impairment (41% of the reviewed literature). Developmental

Coordination Disorder (DCD) emerged as the next most frequent descriptor (26%), followed by terms related to developmental sensori-motor dysfunction (18%) and other terms related to dyspraxia and minimal brain dysfunction (16%).

The variety of descriptors of motor impairment reflects the confusion that has impeded research and communication among health and education professions (Henderson & Barnett, 1998). In an attempt to provide consistency, the APA introduced the term DCD to describe children with a motor impairment. As a consequence, reference to DCD began to consistently appear in published literature by 1992 (Geuze et al., 2001). This partly explains why the term ‘clumsy’ (introduced 50 years before DCD) was more popular in research between 1989 and 1999. Since its introduction in 1987, a refined definition of DCD has subsequently been released, that excluded neurological parameters which took into consideration mental retardation (APA, 1994). The criterion has remained unchanged in the latest test revised version (APA, 2000).

In 1992, the World Health Organisation (WHO) put forward the term “Specific Developmental Disorder of Motor Function”. Generally, ‘motor function’ and ‘coordination’ are terms used interchangeably. However, researchers in the field of motor control describe ‘function’ as a purposeful action in everyday life, whereas ‘coordination’ typically describes how joint muscles behave and interact (Schmidt & Lee, 2005). A focus on motor function may be more appropriate when the identification of motor impairment is of interest. However, for researchers, attention to the specific nature of

coordination may be more appropriate as this may reveal explanations for the manifestations of DCD.

To better understand health and disability, the WHO introduced the International Classification of Functioning, Disability and Health in 2001. This classification system provided a framework for assessing outcomes at three levels: 1) impairment; 2) activity limitations; and 3) participation restrictions. This is in line with the criteria for the classification of DCD put forward by the APA (1994; 2000).

Following the introduction of the refined definition of DCD in 1994 by the APA, Missiuna (2001) has suggested there is now some international consensus amongst researchers and clinicians that the concept of DCD should provide the basic reference for the publication of research or clinical observations. Under the definition, a child who displays the following characteristics would be classified as exhibiting DCD: 1) marked impairment in the development of motor coordination; 2) impairment that significantly interferes with academic achievement or activities of daily living; 3) coordination difficulties that are not due to a general medical condition such as cerebral palsy or muscular dystrophy, and the criteria are not met for Pervasive Developmental Disorder; and 4) where mental retardation is present, the motor difficulties are in excess of levels usually associated with it (APA, 2000, p 58).

However, despite the efforts of the APA, and the reported consensus between researchers and clinicians there remains some evidence that the use of DCD as the definitive

terminology still lacks global support. An investigation to determine the use of the terms, 'clumsy', 'DCD' and 'dyspraxia' by health and educational professionals in the United Kingdom concluded that in this domain the terms 'DCD' and 'dyspraxia' were less familiar than the term 'clumsy'. Amongst those health and education professionals who declared familiarity with all three terms, the consensus was that all were used to describe some sort of overall movement difficulty. Consequently, in the UK at least a divergence of understanding and inter-professional differences in the use of the term DCD remains (Peters, Barnett & Henderson, 2001).

Communication is also made difficult as problems experienced by DCD children are broad and have been linked with "almost any sensory or motor skill imaginable" (Visser, 2003, p 480). Children with DCD have been found to show deficits in the execution of gross motor skills (Dewey & Kaplan, 1992; Henderson, Rose & Henderson, 1992; Raynor, 1998; Skorji & McKenzie, 1997) as well as fine motor skills (Smits-Engelsman, Niemeijer & van Galen, 2001). Generally, gross motor skills are a part of locomotion activities such as running, walking, skipping and jumping. Here, large muscles and most of the body's segments are coordinated to perform gross movements, as opposed to fine movement tasks. Fine motor tasks include writing, doing up buttons and threading cotton through the eye of a needle. These tasks require smaller movements and greater control and precision of the body's segments. Problems in their execution have been attributed to deficits in the sensory domain, the motor domain and sensorimotor integration (Mon-Williams, Pascal & Wann, 1994; Mon-Williams, Wann & Pascal, 1999; Sigmundsson, Invaldsen & Whiting, 1997; Sigmundsson, Whiting & Invaldsen, 1999).

Interestingly, children with DCD have been reported as exhibiting normal visual acuity (Mon-Williams et al., 1994). The visual system has been extensively studied and neural pathways seem to be intact in children with DCD (Mon-Williams, Mackie, McCulloch & Pascal, 1996; Mon-Williams et al., 1999). However, visual perception, attention and memory have all been shown to be poorer in groups of children with DCD than in age-matched controls (Dwyer & McKenzie, 1994; Hulme, Smart & Moran, 1982; Wilson, Maruff & McKenzie, 1997). Among the associated visual problems reported are inaccuracies in estimating object size (Hulme et al., 1982; Hulme, Smart, Moran & McKinlay, 1984; Lord & Hulme, 1988), difficulties in locating an object's position in space (Schoemaker, Van der Wees, Flapper, Verheij-Jansen, Scholten-Jaegers & Geuze, 2001), poor accuracy in moving to targets (van Dellen & Geuze, 1988), poor performance of complex visuospatial and/or visuoperception tasks (Wilson & McKenzie, 1998) such as tracking (Lord & Hulme, 1987) and copying geometric forms into a text booklet (Parush, Yochman, Cohen & Gershon, 1998). Furthermore, a decreased ability to direct visual attention has been reported (Wilson & Maruff, 1996; 1999; Wilson et al., 1997). On the other hand, others have also found abnormalities in the execution of movements, in the absence of any perceptual dysfunction (Hoare, 1994; Hoare & Larkin, 1991; Laszlo & Bairstow, 1983; Raynor, 2001).

2.1.1. Impact of DCD on Daily Activities and Physical Fitness

The effect on daily living experienced by children identified with DCD is relatively mild compared to that experienced by children with neurological problems such as cerebral palsy and spina bifida. Nevertheless, DCD does have significant effects upon children's daily function and academic, psycho-social and vocational outcomes in the long term (Cantell, Smyth & Ahonen, 1994; Bouffard et al., 1996; Hellgren, Gillberg, Gillberg & Enerskog, 1993; Kleiber, 1999; Schoemaker & Kalverboer, 1994; Smyth & Anderson, 2000; Wall et al., 1990; Wilson & McKenzie, 1998).

Motor impairment is linked to under achievement at school (Henderson & Barnett, 1998; Wilson & McKenzie, 1998). This compromised academic performance places children at risk of obtaining lower intelligence scores (Dewey & Wilson, 2001; Smyth, 1992).

Children identified with DCD may exhibit disruptive classroom behaviour in an attempt to gain recognition and friends by compensating for poor academic performance (Smyth, 1992; Waterson, 1999). Adolescents with associated problems of DCD report having fewer friends, more feelings of low self-worth and more anxiety than their peers without DCD. Notably, however, the actual impact of DCD on self-perception is less in younger children than in adolescents (Losse et al., 1991). It is during the process of development, that a marked deterioration in self-perception accompanying DCD may be observed. Less competent social skills, poor motivation, low self-esteem, depression, social isolation, hypoactivity and distractibility are all characteristics associated with DCD. Contrary to common belief, in the absence of early identification and intervention, coordination

difficulties and their associated outcomes can persist in many children and these children will not always “simply grow out of it” (Henderson et al., 1992).

Children who are identified with DCD have been observed as being at a developmentally younger age level than their age-matched peers. Parents have reported that children identified with DCD, for example are immature in their behaviour (Ahonen, 1990). It is possible a tendency towards immature behaviour may serve as a device to protect the adolescent from comparison with their own age group, from taking responsibility for their actions, and thus make them less vulnerable when it comes to societal expectations related to young adults. Self-perception profiles support the perceived protective actions of immature behaviour. (Cantell, Smyth and Ahonen, 2003).

Generally, the problems adolescents with DCD experience can expect to be compounded by lack of involvement in play and sporting activities. These play and sporting activities provide opportunity for social interaction amongst peers. This interaction provides the nervous system with information about movement control. The physical fitness of pre-adolescent children is also developed through play rather than through organised or structured conditioning programs as seen with adolescents or adult populations (Hands & Larkin, 2002). Generally, children each day engage in play and sporting activities. They run, walk, skip, climb, hang, roll, land and jump. The specific type and quality of physical fitness is developed through the frequency, duration and the intensity at which the fundamental movements are performed.

Play for children with DCD can be frustrating and embarrassing; they have an awkward running pattern, fall frequently, drop items (such as balls) and find it difficult to imitate body positions (Miyahara & Register, 2000; Smyth, 1992). Many children with DCD display neurological soft signs such as hypotonia, persistence of primitive reflexes and immature balance reactions that make movement difficult (Dewey & Wilson, 2001; Schoemaker, Hijlkema & Kalverboer, 1994). In addition, slow reaction and movement times have been associated with poor gross motor task performance. This makes the performance of sport related actions such as jumping for distance more difficult (Henderson et al., 1992). At infancy, reflexes and then later in childhood, reaction times are regarded as measures of the integrity of the neuromuscular pathways and the ability of the system to respond rapidly to environmental information/stimuli (Parker & Larkin, 2003). Reaction time is the time elapsed from stimulus to initial movement. It involves stimulus identification and the organisation of an appropriate action but not the execution of that action. The time from initial stimulus to the execution is known as response time and the action component is movement time. Response time tasks have shown that children with DCD have both slower and more variable movement and reaction times than their age matched peers. These differences have been attributed to delays in the motor planning stage (Huh, Williams & Burke, 1998; Raynor, 1998; Smyth & Glencross, 1986; Williams & Burke, 1998; cited in Williams, 2002).

On account of their difficulties in performing movement and a lack of perceived physical competence (Schoemaker & Kalverboer, 1994; Wall et al., 1990), participation in typical childhood activities such as play are generally avoided, and DCD children tend to lead

more sedentary lives (Bouffard et al., 1996; Cairney, Hay, Fraught, Corna & Flouris, 2006; Mandich, Polatajko & Rodger, 2003). As such, low fitness levels (Parker & Larkin, 2003) and increasing levels of obesity (Dewey & Wilson, 2001) have been associated with DCD children, further compounding barriers to the performance of fundamental movements and increasing the degree of difficulty experienced when attempting to learn new skills (Hands & Larkin, 2002; Larkin & Hoare, 1991; O'Beirne, Larkin & Cable, 1994). Hence, a vicious cycle of motor activity avoidance, depression, social isolation and decreased participation in physical activity can emerge in DCD children (Rasmussen & Gillberg, 2000).

This relationship between participation in physical activity and the level of motor proficiency has driven the development of descriptors such as “activity deficit hypothesis” or “hypoactivity” (Bar-Or & Rowland, 2004; Bouffard, et al., 1996; Li & Dunham, 1999; Stratton & Armstrong, 1991; Thompson, Bouffard, Watkinson & Causgrove-Dunn, 1994). Work has shown that children with poor coordination skills use playground equipment less often and participate in vigorous physical activities significantly less compared to well co-ordinated children (Bouffard et al., 1996). Even when physical activity is provided during physical education lessons, children with coordination difficulties were found to be active in moderately vigorous activity for less time (17.9%) than children with moderate competence (20.3%) or high competence (22.3%) (Li & Dunham, 1999). Children with poor motor proficiency have been found to be less active and vigorous in out of school hours compared to matched controls (Kuiper, Reynders & Rispen, 1997). In addition, children with low motor proficiency have been

found to be more interested in fine manipulative activities and to select passive activities for their after-school activity (Rarick & McKee, 1949). The activities chosen by the children identified with DCD required less energy expenditure than those involving more gross motor movements, further supporting the findings of avoidance of physical activity in that particular group. Heart rate monitoring has provided yet more evidence for the relationship between movement competence, habitual physical activity and fitness levels in children with poor motor skills (Stratton & Armstrong, 1991). During physical education lessons for example, motor impaired children were found to spend less time with heart rates above a moderate level of intensity (159 beats per minute) than children of average or high ability (19%; 23%; 31% respectively).

Although a relationship between sedentary lives and obesity in children with motor impairment has been widely observed, it is unclear as to whether this relationship is a 'cause or effect'. Children identified with DCD have been found to be significantly heavier (Visser et al., 1998) and have a higher Quetelet index (Hammond & Dickson, 1994). Specifically, a high Quetelet Index indicates relatively thicker limbs and torso caused by increased fat mass rather than lean body mass due to the low levels of circulatory androgens available in pre-pubertal children. From a sample of seventeen primary school aged children identified with DCD, eleven of the children were reported to have a higher than acceptable percentage body fat (Hammond & Dickson, 1994), with five participants classified as obese (2 males: 3 females). Other work with similar sized groups, found DCD children to be heavier and have a greater percentage of body fat than controls (Larkin, Hoare & Kerr, 1989; O'Beirne et al., 1994; Wasmund-Bodenstedt,

1988). In addition, a higher endomorphic component of the somatotype rating (described by Carter, 1980) was found in DCD children (Larkin et al., 1989; Raynor, 1998) when compared to controls. It is unclear as to whether the greater body mass, higher body fat and endomorphic characteristic reflects withdrawal from physical activity or some other issue such as poor diet (Larkin & Hoare, 1991). However, it seems plausible that hypoactivity among children with DCD may contribute to higher levels of body fat (Hands & Larkin, 2002).

Greater body mass and inefficient movement patterns common to children with motor impairments increase the energy demands of typical movements performed daily. As a consequence, repetition of such movements for DCD children can cause the onset of fatigue much earlier than in well-coordinated peers (Hands & Larkin, 2002). Muscle fatigue has been found to occur earlier in children with motor impairment compared to aged matched controls (O'Beirne et al., 1994). Muscle fatigue was measured as a decrement in force and power output over time. Interestingly, the difference between groups increased with the age of the children. The increasing difference between groups reflected greater decrements in force and power at the older age groups in the DCD children, whereas for their well-coordinated peers, the decrement was reduced with age. Because the movement patterns of DCD children are inefficient, simple tasks that others take for granted require more energy (Ward, 1994) and cause earlier onset of fatigue compared to controls (Hands & Larkin, 2002).

Hammond and Dickson (1994) assessed the physical fitness of DCD children aged 6 and 7 years ($n = 17$) using a battery of performance based tests. From the median scores it was concluded that, in general, fitness levels of the DCD group were low with the exception of the measure of flexibility. Leg power was assessed by the jump and reach test protocol and the group's median score was equivalent to the 25th percentile from the normative data. Of particular interest, however, was the wide range of jump scores within the DCD group (1st -90th percentile). A similar distribution of jump scores was reported for a larger sample of 59 DCD children (Larkin & Hoare, 1991). The wide distribution of scores indicates that some individuals with DCD may be equal to or even surpass TD children in jump performance. DCD children who scored highly on particular measures were generally few (Larkin & Hoare, 1991; Visser, 2003). Therefore, a normal distribution of the group data was not observed. Under these circumstances, differences between mean and medium scores will be relatively large (i.e., $> 10\%$) (Peat & Barton, 2005).

Interestingly, Hammond and Dickson, (1994) found the group of DCD children scored significantly higher than controls on the sit and reach flexibility test. This finding was presumed to reflect a low level of muscular strength, indicating poor control and intermuscular coordination. Therefore a potential risk of hyper-mobility in the lower limb joints during jumping and other ballistic activities may exist in DCD children. At take-off during jumping for example, the orientation of the segments is determined by control and intermuscular coordination. As part of the joint protective mechanism, leg stiffness (K_{leg}) is increased by muscle co-activation to decelerate the joints near end-

range to prevent hyper-extension (Jacobs, Bobbert & van Ingen Schenau, 1996; Jaric, Blesic, Milanovic, Radovanovic, Ljubisavljevic & Anastasijevic, 1999; Siff, 2000). Poor control and intermuscular coordination can result in insufficient K_{leg} and failure to reduce the angular velocity of the joints which in turn permits ‘overshooting’ of the predetermined target angle. This results in hyper-extended joints at take-off, poor performance and an increased risk of injury (Bobbert & van Soest, 2001; Bobbert & van Ingen Schenau, 1988; Haguenaue, Legreneur & Monteil 2005).

2.2. Prevalence of DCD

Worldwide, between five and ten percent of children are believed to meet the diagnostic criteria for DCD (APA, 2000; Gubbay, 1975; Hendersen & Hall, 1982; Kadesjo & Gillberg, 1999; Keogh, 1968; Larkin & Rose, 1999; Sovik & Maeland, 1986). The estimated prevalence of DCD makes it one of the most common childhood disorders comparative to dyslexia and attention-deficit-hyperactivity disorder, and considerably more common than autism or autism spectrum disorders (APA, 2000; Cairney et al., 2006). It is estimated that only a fraction of DCD cases are identified. Factors such as financial constraints, time requirements for screening, the confusion caused by the lack of clarity of the descriptor and the lack of recognition of its significance, all confound the estimation of the prevalence of DCD (Hay et al., 2004).

Traditionally, boys have been more commonly reported to have DCD than girls (Gordon & McKinlay, 1980; Henderson et al., 1992; Kadesjo & Gillberg, 1999; Miller, Missiuna,

Macnab, Malloy-Miller & Polatajko, 2001; Schoemaker & Kalverboer, 1994). However, figures from clinical referrals imply that this gender bias is diminishing (Parker & Larkin, 2003). A ratio of one girl for every nine boys (1:9) was found in 1986, 1:5 in 1990 and 1:3 in 2001. According to Parker and Larkin, higher reported prevalence of DCD in males may be partly due to sampling issues. Studies involving larger samples, for example, have found a more equal gender distribution for impaired motor proficiency (Gubbay, 1975; Larkin & Rose, 1999). These figures do not however, include clinical referrals. Gender bias differences in referrals are not fully understood. A possible explanation may be higher parental expectations of motor performance and sporting achievement for boys in comparison to girls (Parker & Larkin, 2003). It is plausible that parents, health and education professionals notice boys who appear poorly coordinated and overlook girls with similar impairment (Revie & Larkin, 1993).

2.3. Assessment of DCD

As noted above, caution is advisable when reviewing statistical reports of DCD prevalence, as a range of methods have been used to identify children with DCD. Moreover, children recognised as DCD from clinical referrals are not always recognised as DCD when assessed using standardised assessments (e.g., Maeland, 1992). The measurement of motor proficiency uses normative data to classify children as motor impaired or normal. Over 45 movement assessment batteries exist to assess movement skills with each sampling different areas of motor performance (Burton & Miller, 1998). One of the many issues relating to the assessment of DCD is the absence of a test for

DCD that enjoys the status of the Wechsler Intelligence Scale for Children (Wechsler, 1977) in the cognitive domain (Henderson & Barnett, 1998). In spite of the absence of a gold standard test of motor impairment, the M-ABC (Henderson & Sugden, 1992), the McCarron Assessment of Neuromuscular Development (McCarron, 1997), the Test of Motor Impairment (Stott, Moyes & Henderson, 1984), the Bruininks-Oseretsky Test of Motor Proficiency (Bruininks, 1978), and the Southern California Sensory Integration tests of Ayres (1989) comprise the most frequently used standardised tests.

A clinically recognised screening tool of motor impairment is the Movement Assessment Battery for Children (M-ABC: Henderson & Sugden, 1992). The popularity of the M-ABC for identifying and classifying movement disorders in children has been well documented (Smyth & Mason, 1997; Wilson, 2007). This assessment tool separates the components of motor proficiency into measures of manual dexterity, ball skills, dynamic and static balance. A total of 32 items are divided into these four components of motor proficiency. In accordance with the age-stage motor development theories, the level of difficulty of the activities used is graded for the specific ages. Age-band one items are designed for use with four to six year old children, age band two for seven and eight year olds, age band three for nine and ten year olds and age band four for eleven and twelve year olds. Within each age band, the structure of the test is identical. All participants complete three items involving the use of both hands, two items that assess reception and projection of moving objects and three which assess static and dynamic balance.

On completion of the M-ABC the child's performance can be scored in several ways. Raw scores, such as the number of seconds taken to complete the task or number of catches made are noted. The raw scores can then be transformed into scaled scores in order to ascertain where the child's performance lies in relation to the standardised sample (Henderson & Sugden, 1992). This can be achieved at the level of the individual item (assessment task), on each of which the children receive a score of between 0–5, sub-scores (manual dexterity, ball skills and balance) or total score (maximum of 40). The total score as a percentile is the measure most commonly used to determine the level of impairment.

The absence of an agreed gold standard for motor impairment raises the issue of test validity. A concern amongst researchers and clinicians is the lack of reported agreement between tests which suggests that they do not measure the same construct of motor proficiency/impairment. This lack of agreement is illustrated in a study which compared the M-ABC with the Bruininks Oseretsky Test of Motor Proficiency (BOTMP) (Crawford, Wilson & Dewey, 2001). One third of the children classified as having DCD by the BOTMP were not identified by the M-ABC, whereas one quarter of children classified as DCD by the M-ABC were not identified as such by the BOTMP. The levels of agreement failed to reach the criterion of 80% set by the authors. Further the Kappa values were only in the fair to good range of agreement for the BOTMP (battery composite) compared with M-ABC (proportion of observed agreement (PO) = 72% and Kappa = 0.46). Crawford et al. concluded that their findings show that children can score within the average range for one assessment of motor impairment, but be scored as

impaired on another. Thus, although the M-ABC and BOTMP are both assessments used to measure motor impairment in children, when performed on the same sample they classify children differently.

There are two issues that may account for the different outcomes of the BOMPT and M-ABC. Children who rely on external controls perform better on the BOMPT as this assessment permits the researcher to verbally prompt the participants and correct the child during the assessment (Barnhart, Davenport, Epps & Norquist, 2003). Although practice is allowed before the M-ABC is administered, prompting during testing is not. Therefore, children with attention difficulties may find performing on the M-ABC tasks to be more challenging as the performance is influenced by the retention of the instructions given to them by the researcher prior to testing. This may explain why the M-ABC tends to identify more children with DCD than BOTMP (Dewey & Wilson, 2001) and that children identified by the M-ABC tend to have additional attention problems (Wilson, Polatajko, Mandich & McNab, 1998).

The actual items contained within a testing protocol can affect the child's percentile score. Everyday tasks are used to assess fine and gross motor skills. However, although everyday self-help tasks such as tying shoe laces or using a knife and fork can be assessed quantitatively, lack of knowledge of the child's past experience at home or in school makes it difficult to interpret failure when it occurs (Barnett & Henderson, 1992). An assumption is made for the testing protocol that children will perform the tasks used to assess their motor abilities in a set manner. That is, there is one basic solution to the

task and all children are aware of this. Yet, for example, assessment of handwriting may become problematic unless there is knowledge of how the child has been taught and whether additional literacy problems exist (Barnett, 1994).

The presence of motor impairment can be suggested by using a cut-off criterion from the M-ABC scores (Miyahara et al., 1998). Yet, the test fails to measure the quality of movement (Kaplan et al., 1998). Further insight to the degree of impairment, can be achieved by using the checklist that accompanies the M-ABC (Henderson & Sugden, 1992). This checklist allows competencies of daily activity to be rated. Unfortunately, the descriptions of expected normal or abnormal performances in the checklist are broad, leaving ample room for interpretation, making classification of DCD rather difficult (Henderson & Barnnet, 1998; Sugden & Wright, 1998).

Interpretation of the motor impairment literature is difficult due to this lack of consensus concerning inclusion criteria. From a review of publications on the study of DCD, only 60% had objective inclusion criteria (Geuze et al., 2001). Recommendations were made that a child scoring below the 15th percentile on standardised tests of motor skill and having an IQ score above 69 would qualify for a diagnosis of DCD. Within the clinical definition of DCD an evaluation of IQ is therefore included. In mainstream school testing programs motor impairment alone may be a more appropriate descriptor because of inconsistent inclusion of the IQ assessment. Disagreement exists throughout the literature, as to whether children with motor impairment perform poorly on IQ tests relative to their verbal IQ because of the motor responses required in some performance

tasks of IQ tests (Henderson & Hall, 1982). For example, motor impaired children who were within the normal range for IQ, scored towards the lower end of the normal range (Cantell et al., 1994; Lord & Hulme (1987).

It has been noted that children with DCD should be able to complete most of the tasks, but the quality and speed will be below that of their peers (McConnell, 1994; Missiuna & Pollock, 1995). The M-ABC and other tests of motor proficiency however, fail to measure the quality of movement (Kaplan, Wilson, Dewey & Crawford, 1998). The M-ABC has the advantage of reliably identifying difficulties with proprioceptive matching and aiming (Smyth & Mason, 1997). However, test reliability of the M-ABC decreases with age. Measurement reliability of up to 97% has been reported for 5 year-olds and 73% for 9 year-olds (Hill, Bishop & Nimo-Smith, 1998). In addition, the M-ABC has been described as ‘on-going’ and not yet complete (Miyahara et al., 1998) with data collected from the USA, Canada, UK, Netherlands, Sweden and Hong Kong (e.g., Rösblad & Gard, 1998; Smits-Engelsman, Henderson & Michels, 1998). Ethnic origin, education experience and socio-economic status are all important variables that can affect the validity of the M-ABC (Chow, Henderson & Barnett, 2001; Mayson, Harris & Bachman, 2007; Miyahara et al., 1998). Recently, the M-ABC was revised and the second edition reportedly involved more substantial validation procedures, thus improving the accuracy of assessment (Henderson, Sugden & Barnett, 2007).

For some, DCD is a relatively generalised problem, and this will be reflected in the motor impairment across all item scores in the M-ABC. It is, however, common to find within

the DCD group, individual children who, on particular measures perform at levels expected for TD children (Wright & Sugden, 1996). It is quite possible, therefore, that differences in developmental outcomes amongst children with DCD reflect the existence of subgroups. From the DCD literature, evidence is available to support the existence of subgroups of DCD which are heterogeneous in nature (Smyth & Mason, 1998). This means that DCD children will display varying patterns of impairment and simple comparisons of an undifferentiated DCD group and controls may be unjust and of limited value.

Early ‘subgroup’ research has focused on the descriptive analysis of the motor characteristics of children within the DCD population (Gubbay, 1975; Henderson & Hall, 1982). Identifying subgroups on the basis of functional deficits has been the primary focus of this approach. Wright and Sugden (1996) identified five subgroups, including one subgroup that was poor at catching and another that was poor at manual dexterity and balance. Dewey and Kaplan (1994) have differentiated on the basis of whether difficulties were in planning or execution. Finally, cluster analysis from a wide range of assessments has also been used to identify subgroups of children with DCD (Dewey & Kaplan, 1994; Hoare, 1994; Miyahara, 1994). However, each of these three studies has differed in the number and characteristics of the subgroups of DCD. Hoare’s study isolated five subgroups around the concept of visual perception, visuomotor integration, manual dexterity, kinaesthetic acuity, balance and running speed. Whereas, Dewey and Kaplan (1994) categorised on the basis of balance, bilateral coordination, upper limb coordination, transitive gestures and motor sequencing, this approach resulted in four

subgroups. Miyahara (1994) also identified four subgroups, but using the dimensions of running speed, agility, balance, strength, upper limb speed and dexterity. More recently, balance has been investigated as a characteristic of a subgroup (Geuze, 2003; Huh, 2001; Wann, Mon-Williams & Ruston, 1998). Wann et al. studied postural sway in relation to a moving environment and reported a sub-group of children with DCD who had balance difficulties and who used visual information for balance more than others did. Difficulties in balance and posture control will be discussed in more detail later.

Although DCD subgroups have been identified, some researchers still argue that DCD children show general impairment across tasks, but within subsets of the tasks, some show specific deficits (e.g., Dewey & Kaplan, 1994; Hoare, 1994; Macnab, Miller & Polatajko, 2001; Wright & Sugden, 1996; Visser et al., 1998). One common factor between such studies has been the specific difficulty displayed by DCD children in sensorimotor measures. Possibly where a generalised sensorimotor deficit exists, a subgroup of DCD may be present, formally known as demonstrating a generalised perceptual dysfunction (Hoare, 1994). Such a subgroup will emerge, regardless of the specific sensorimotor variables used in the study, whereas the presence of other subgroups depends entirely on the inclusion and combination of particular measures (such as balance).

2.4. Growth and Long Term Issues for DCD Children

Growing children experience relatively large and rapid changes to limb lengths that can temporarily challenge co-ordination and balance control (e.g., Shepard, 1981; Tanner, 1978). Coordination tasks that are dependent on a finely calibrated sensorimotor system therefore, can be disrupted during growth. In a study involving TD and DCD children Visser et al. (1998) only found evidence of such a disruption in the TD children. This longitudinal study lasted two and a half years and assessed the motor proficiency of a group ($n = 37$) of boys aged 11.5 years (at the start of the study) using the M-ABC every six months (Visser et al., 1998). The M-ABC total scores were aligned to Peak Height Velocity (PHV). The DCD group's performance improved throughout the entire duration of the study. In contrast, motor performance in the TD group did not improve in a linear fashion, but following the onset of the growth spurt displayed a decline in motor performance. Therefore, the rate of motor development during the growth spurt was related to the initial level of performance before the spurt (Beunen & Malina, 1988; Roede & van Wieringen, 1985; Visser et al., 1998). The children who were well coordinated were at risk of compromised motor performance during the growth spurt, unlike those children who were initially poorly coordinated.

Other studies have shown that physical growth can benefit children identified with DCD at an early age, and that some DCD children have been found to experience improved motor abilities through a period of physical growth especially during adolescence (Soorani-Lunsing, Hadders-Algra, Huisjes & Touwen, 1994; Visser et al., 1998). Such

enhanced motor performance has been hypothesised to show the adaptive outcome of the functional Central Nervous System (CNS). This proposes that initial mismatch between neural representations of the skeletomuscular system and body morphology becomes 'corrected' as the metrics and dynamics are recalibrated (Visser et al., 1998). An alternative explanation is that, at the onset of puberty, the degree of myelination increases mediated by hormonal adjustments such as thyroxine and estrogen, giving rise to an improved motor performance (Hadders-Algra, 2002). Further possibility is that if normal functioning does not follow, over time an adaptive behaviour may emerge through experience. In this case, there is a process of 'tuning' the various parts of the system, while the parts themselves continually change as a result of physical and neural development (Sporns & Edelman, 1993). Therefore, with experience during adolescence, a 'levelling out' of earlier identified differences may occur.

As a result, historically many parents have been told that children identified with DCD will 'grow out of it' as they mature (Losse et al., 1991). However, although maturation may vary with age and development, in some cases, lack of coordination continues through adolescence and into adulthood (APA, 1994; 2000; Cantell et al., 2003; Coleman et al., 2001; Losse et al., 1991; Rasmussen & Gillberg, 2000; Schoemaker et al., 2001; Smyth, 1992; Sugden & Chambers, 1998). Certainly, some favourable developmental outcomes have been reported. For example, only a third of children with DCD remained uncoordinated in one eight year follow-up investigation (Knuckey & Gubbay, 1983). Furthermore, Visser et al. (1998) reported that on each sub-section of the M-ABC the majority of boys identified with DCD had caught up with the controls to some extent by

the time they were aged 14-15 years. However, closer examination of this study shows that the motor impaired group's mean improvement could be accounted for by the performance of five participants representing 30% of the group. Four of the other children from the DCD group still failed the criteria for twelve year-olds at the age of fourteen years. Other longitudinal studies have shown that around 50% of adolescents still had perceptual motor problems following classification during early childhood (Cantell et al., 1994; Loose et al., 1991). Therefore only half of the children initially identified with DCD 'grew out of it'.

Cantell et al. (2003) put forward the proposition that children with DCD follow one of two distinct pathways: persistence or resolution. This was based on an extension of their earlier longitudinal work using children (Cantell et al., 1994; Lyytinen & Ahonen, 1989), who at the end of the study had reached the age of 17 years. All participants were originally from one Finnish town. They were selected on the basis of early milestone data and perceptual motor skills at the age of five years (DCD $n = 106$; Controls $n = 40$). At the age of 15 years these children were reassessed, and their scores used to characterise the three groups for the 2003 study. The three groups included: a DCD group ($n = 22$); an intermediate group ($n = 23$) and a control group ($n = 20$). The criteria for the DCD group included one of the following: a score on one task 4.5 standard deviations (SD) below the mean of the control group, three scores of 2.5 SD below the mean of the control group, or five scores below 1.5 SD. The intermediate group comprised children who at the age of five years were identified as DCD but, based on the criteria given, at 15 years were now no different to the control group. The testing of the three groups involved two

questionnaires, a structured interview, eight perceptual motor tasks (Table 2.2) and an IQ test.

Table 2.2: Perceptual motor assessments used by Cantell et al. (2003) for children at the age of 17.

Perceptual motor area	Assessment	Type of record
Balance	Walking heel-to-toe (Henderson, Geuze & Losse., 1990); Test of motor impairment – second Henderson revision)	Number of steps (max 15)
Ball skills	One-hand catch (Henderson et al., 1990; Test of motor impairment – second Henderson revision)	Number of catches (max 10 for each hand)
	Hitting wall target (Henderson et al., 1990; Test of motor impairment – second Henderson revision)	Number of goals (max 10)
Speeded fine motor tasks	Purdue pegboard (Wilson, Iacoviello, Wilson & Risucci, 1982) Repeated finger- thumb opposition (Denckla, 1973)	Number of pegs in 1 minute (max 100)
Visual-motor tasks	Dynamic hand coordination (Luria, 1980; Golden, 1981; Luria, 1980)	Mean number of three different movements in 10 s
	Copying geometric figures (developmental test of visual-motor integration = VMI: Berry, 1982)	Number of correct drawings (7-21 points)
Kinaesthesia tasks	Kinaesthetic feedback from positions (a neuropsychological assessment of children; Korkman, 1988)	Correct positions (0-3 points)

The main findings from this study were:

- The DCD group performance was inferior to that of the control group in all perceptual motor tasks with the intermediate group situated between the two. This suggests that significant difficulties present at 15 years will persist through adolescence. Further, despite some DCD children in the study previously having a significant difficulty in only one task, the differences had now become spread across a variety of tasks.

- The intermediate group caught up to the control group on most perceptual motor tasks. Those tasks which did not differentiate between the DCD and intermediate groups were, hitting the wall target (Henderson et al., 1990) and visual–motor integration (Berry, 1982). The lack of improvement in these two perceptual tasks may reflect the intermediate group’s avoidance of certain sporting activities (e.g., Cairney et al., 2006).
- Based on discriminative functional analysis, changes in classification from the intermediate to the control group occurred in some participants between the ages of 15 and 17 years. At 17 years of age, 74% of the participants were still correctly classified from the variables collected at the age of 15. The authors suggest that this shift in classification demonstrates that the distinction between the intermediate and control groups decreased with age. Therefore, some children in the intermediate group caught up and ‘grew out’ of their motor impairment by the age of 17.
- Lower Weschler Adult Intelligence Scale scores (Finnish short form version, Sattler, 1992; Wechsler, 1974) were found in those adolescents classified with DCD. The DCD group also had the shortest school careers of the three groups.

Developmental Coordination Disorder can continue into adulthood and the level of impairment can range from minimal to profound. A study by Cousins and Smyth (2003)

on the effects of motor impairment in adulthood, modelled several tasks from a battery of tests developed for 11-12 year-old children. Slower performance across a range of tasks in comparison to their age-matched controls was observed for the motor impaired group. Movement time was profoundly affected, more so than reaction time, suggesting that planning was less problematic than the execution of movement. This is consistent with other DCD studies with children (e.g., Henderson et al., 1992). In addition, the motor impaired adults completed tasks using unusual or suboptimal movement patterns to compensate for poor balance control.

2.5. Posture and Balance Control

Posture and balance control of the body segments is essential to efficient movements. In their study of adults with motor impairment, Cousins and Smyth (2003) demonstrated the importance of posture and balance control. They found that when participants remained seated, thus reducing balance and postural control demands, manual dexterity and visuo-constructional tasks were generally more proficient than when whole body movement was required. If movement difficulties can be overcome by reducing the postural and balance demands of tasks, this may explain why sub-optimal compensatory movements give the appearance of 'clumsiness' in those identified with DCD (Cantell et al., 2003).

Posture and balance depends on the control of body segments by the use of complex orchestrated efforts between feedback and feedforward mechanisms within the central and peripheral nervous systems. These mechanisms are, however, task specific (McGill,

2002; Williams & Woollacott, 1997). Balance control under a static condition, for example, is reliant upon keeping the centre of mass within the limits of the support. In the case of static balance, the time available is long enough in duration that feedback can be used to make adjustments to maintain equilibrium. In the case of dynamic balance, the centre of mass of the body moves beyond the limits of the support for brief periods of the movement task. Activities such as hopping or jumping for distance, for example, require this movement of the centre of mass beyond the base of support. In the case of explosive jumping movements the time available during the concentric phase is insufficient to make adjustments from feedback mechanisms. Therefore feedforward mechanisms or preplanning becomes essential, which for DCD children has been previously identified as problematic when performing movements (e.g., Henderson et al., 1992; Johnston, Burns, Brauer & Richardson, 2002).

It has been observed that children with motor impairment often suffer from poor postural control and balance skills (Geuze, 2003; Wann et al., 1998; Williams & Woollacott, 1997). Johnston et al. (2002) examined the onset of activation of selected trunk and shoulder muscles during a rapid, voluntary, goal-directed arm movement by children identified with DCD. The assertion from Johnston et al. was that the trunk muscles would activate in anticipation of a rapid arm movement initiated by the Anterior Deltoid. This was based on the notion that co-activation of the anterior and posterior trunk muscles preceding or at the same time as the Anterior Deltoid activation is required in the role of stabilising the trunk prior to arm movements (Hodges & Richardson, 1996). This anticipatory onset of the trunk muscles therefore, exhibits the presence of a feedforward

mechanism, which was observed in the TD group. In the DCD group, however, activation was delayed until after the Medial Deltoid activation in three of the four anterior trunk muscles. Although, these findings are specific to this activity, the absence of anticipatory postural activity in the anterior trunk muscles found in the DCD group may provide a key to poor performances in more complex tasks involving the whole body.

During explosive movements involving the whole body, dynamic balance is autonomously controlled, requiring inter-muscular coordination for efficient and effective movement of the limbs (McGill, 2002). Poor inter-muscular coordination can result from ineffective postural control leading to unwanted muscle activation (Johnston et al., 2002; Williams, Fisher & Tritscher, 1983). In such instances, co-activation of both agonist and antagonist muscle groups increase musculoskeletal stiffness across joints (Basmajian & De Luca, 1985), which may contribute to the apparent clumsiness of DCD children (Geuze, 2003; Raynor, 1998; 2001).

Inefficient muscular activation patterns appear to underlie the balance control problems of children identified with DCD. This concept is supported by findings of prolonged agonist activation, greater temporal inconsistency between electromyography (EMG) parameters and increased movement time (Huh et al., 1998). Prolonged activation which causes joint stiffness also increases energy expenditure and promotes the early onset of fatigue during activity (Hands & Larkin, 2002). Under co-contraction conditions a desired movement will require the agonist to be activated to a higher level to counteract the opposing muscle group(s). Williams et al. (1983) showed, for example, that children

with motor impairment increased the activity of the soleus and gastrocnemius muscles whilst standing. They proposed that restricted motor development was a result of insufficient improvement of inter-muscular control with age in the DCD children. In contrast TD children displayed gradual refinement of control as they aged.

From a neurological perspective poor balance control may be an indicator of cerebellum impairment. The cerebellum is essential for postural control and any dysfunction will disrupt balance and limb movements. Poor balance control in children with dyslexia has been attributed to cerebellum deficits (Nicolson & Fawcett, 1999; Nicolson, Fawcett & Dean, 2001). Cerebellum dysfunction has also been associated with poor movement by disrupting the initiation of body segments and timing (coordination) patterns (Ivry, Keele & Diener, 1988; Piek & Skinner, 1999; Salman, 2002; Williams et al., 1983). Although the aforementioned research was specifically directed to dyslexia, problems of muscle tone regulation (Raynor, 2001), balance control (Geuze & Kalverboer, 1987; Piek & Skinner, 1999) and timing are well known in the field of DCD. For those children identified with DCD, non-optimal cerebellum function may affect the development of autonomous control of balance and contribute to the movement problems (Geuze, 2003). The irregular muscle innervations can result in loss of movement control and may also reduce ability to adapt to task constraints, especially when the speed of the task is increased (Cousins & Smyth, 2003).

Previously, balance skills have been shown to be poor in a high proportion of children with DCD (van Dellen & Geuze, 1998; Visser et al., 1998; Wann et al., 1998). Static

balance and static postural control were poor in children and adolescents with impaired motor proficiency (Cantell et al., 1994; Hoare 1994; Williams et al., 1983). Armitage (1993) found that children with DCD (n = 40) maintained static balance for a shorter duration than controls. Although the mean maximal one-foot static balance time increased with age in the DCD group (11.4 s in the 5 to 6 year old and 18.5 s in the 8 to 9 year old DCD groups), both groups had shorter balance times than the younger and older controls (21.3 s and 29.2 s respectively). Moreover, increased sway of the centre of pressure measures derived from a forceplate was reported for the DCD children, indicating difficulties in using corrective strategies to maintain balance control.

Geuze (2003) used the M-ABC static balance and balance scores to characterise a group (n = 24) of DCD children with balance problems (DCD-BP). When members of the DCD-BP group were compared to age-matched DCD controls that scored well on the M-ABC balance tests, they were found to have poor balance control and a reduced adaptive capacity for novel perturbations compared to controls. Specifically, DCD-BP children displayed: 1) greater excursions of the Centre of Pressure (COP) in the lateral direction when standing on one leg with no vision; 2) greater activation of the muscles around the ankle joint and an increased co-activation of the muscles of the upper and lower leg when balancing; 3) an extended delay in response to the first unexpected perturbation (Geuze, 2003).

For forceplate measures taken during single leg stance and without vision, the excursions of the centre of pressure in both lateral and anterior-posterior directions of the children

with DCD-BP resembled the performance of the younger TD group. Generally, the differences between DCD-BP and controls were small, (no effect size was reported). Despite the small differences, the author concluded that the tests were sensitive for the purposes of the clinical study with children in the same age range (Geuze, 2003). Furthermore, it was speculated that children identified with DCD-BP did not display an automated control of balance to the same extent as the control children.

In summary, children identified with DCD have movement difficulties, which affect their present life and their future. The term ‘DCD’ was introduced in 1987, in a hope to replace the descriptor ‘clumsy’. Since its introduction, there is some evidence that it is becoming adopted by both clinicians and researchers who deal with children. Identification can be problematic, and there are a number of acceptable ways to characterise these individuals, ranging from clinical referrals to long form motor assessments. In addition, not one of the motor tests is established as a gold standard, and when common tests are compared they characteristically do not identify the same cohort. One explanation for the discrepancy between assessments may be how the test is presented to the child. More appropriately it is noted that for some, DCD is a broad disorder covering a wide spectrum of motor tasks, where, for others it can be more specific. Therefore for those who have specific difficulties, performance in other motor tasks may be no different compared to those of TD. For the purposes of this study the M-ABC total impairment score will be used to characterise TD and DCD groups, using the cut-off of 15th percentile (Hendersen & Sugden, 1992).

CHAPTER III
LITERATURE REVIEW
PART II: VERTICAL JUMPING

Vertical jumping has been identified as one of the fundamental movement skills (Gallahue & Ozmun, 2002). It is well practised, familiar and part of everyday physical activity for children aged between 5 and 12 years. The most effective strategy to gain maximal jump height from quiet stance involves a countermovement with a coordinated arm-swing (Harman, Rosenstein, Frykman & Rosenstein, 1990). The coordination pattern of vertical jumping for humans is common and one optimal solution exists (Bobbert & van Ingen Schenau, 1998). The recognised movement pattern of vertical jumping is stable and emerges in most TD children by the age of 3 years (Jensen et al., 1994). Finally, vertical jump has been used as a well recognised and common assessment of lower limb explosive strength (Sayers, Harackiewicz, Harman, Frykman, & Rosenstein, 1999). Jump height, the performance outcome measure, however, is influenced by the anatomical and physiological diversity of the individual, combined with practice (Bobbert & van Ingen Schenau, 1988). The following section will describe vertical jumping and the key contributions to its performance in detail.

3.1. Description of Vertical Jumping

The stereotypical movement pattern executed during a vertical jump is shown in Figure 3.1. The movement pattern consists of an eccentric phase where the shoulders are

extended and the hip, knee and ankles are flexed to create a downward movement known as the countermovement. During the eccentric phase the muscle-tendon complex is stretched and energy is stored. Transition from the eccentric phase to the concentric phase occurs immediately prior to the lowest point of the countermovement (position 3). The concentric phase, starts from the lowest point of the countermovement and involves flexion at the shoulders to bring the arms forward. In addition, a distal to proximal sequence of the lower limb joint extensions creates the upward displacement of the body's Centre of Mass (COM). At take-off, the arms are orientated above the horizontal with the lower limbs near full extension.

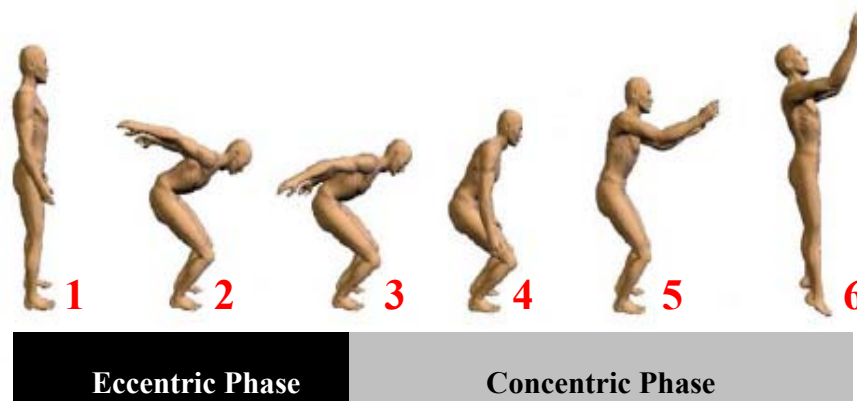


Figure 3.1: Key body placements during the countermovement jump with arm-swing (adapted from Lees, Vanrenterghem & De Clercq, 2004).

At quiet stance, before the initiation of the movement, Vertical Ground Reaction Force (VGRF) is equal to Bodyweight ($\text{Weight} = \text{Mass} \times \text{Gravity}$). Following the first movement, the eccentric phase begins and the VGRF falls below bodyweight (BW), this period is commonly known as 'unweighting' and continues until VGRF equals BW. The body continues to move downwards until the low point of the countermovement is reached. During this time energy is stored. From the low point, the concentric phase starts

which involves the rapid upward movement of the COM. During the concentric phase, the lower limbs extend reutilising the stored energy but also actively producing VGRF until the instant of take-off where the lower extremity joints are near full extension. For well coordinated jumping, jump impulse, the total of VGRF produced above bodyweight determines the vertical velocity of the centre of mass (VCOM) at the instant of take-off and thus jump performance.

3.2. Key Contributions to Jump Height.

3.2.1. Vertical Velocity

The VCOM at take-off is fundamental to vertical jump performance (Aragón-Vargas & Gross, 1997a, 1997b; Bobbert & van Soest, 1994, 2001; Bobbert & van Ingen Scheau, 1988; Bobbert & van Zandwijk, 1999; Dowling & Vamos, 1993; Fukashiro & Komi, 1987; Harman et al., 1990; Hay, 1993; Hudson, 1986; Khalid, Amin & Bober, 1989; Kollias, Hatzitaki, Papaiakevou & Giatsis, 2001; Luhtanen & Komi, 1978; Miller & East, 1976; Oddsson, 1989; Payne, Slater & Telford, 1968; Shetty & Etnyre, 1989). From the impulse-linear momentum relationship, more force over time produces a larger resultant impulse, increasing the change in linear momentum (Miller, 1976). Therefore, a greater jump impulse will lead to a greater VCOM at take-off and correspond to a higher vertical jump (Aragón-Vargas & Gross, 1997a; Vanrenterghem et al., 2004). This, however, is based on the assumption that the jump is well coordinated (Bobbert & van Soest, 2001) and although generally correct for children of three years and above (Jensen et al., 1994),

it may not be the case for motor impaired children (Falk, Eliakim, Dotan, Liebermann, Regev & Bar-Or, 1997).

3.2.2. Countermovement (Eccentric)

A coordinated flexion of the hip, knee and ankle joints results in the eccentric phase of the countermovement (Figure 3.1, positions 1, 2 and 3). A brief transition phase follows before a rapid extension of these joints creates the upward movement of the body that ultimately produces flight. Research has compared a countermovement jump to a squat jump in order to demonstrate the enhanced performance obtained from this preparatory phase (e.g., Enoka, 1988; Harman et al., 1990; Khalid et al., 1989). A squat jump involves the participant lowering the body down and holding the crouch or squat position for a short period before initiating an upward movement. No countermovement is permitted. When directly compared, countermovement jumps produced approximately ten percent greater height than the squat jumps in adult populations (e.g., Enoka, 1988; Harman et al., 1990; Khalid et al., 1989). The increase in jump height can be explained by an increase in the muscle pre-load on the lower extremity evoked by the countermovement. Pre-loading enables the muscular system to utilise the stretch shortening dynamics of the muscle-tendon complex which allows the build up of force before contraction (Anderson & Pandy, 1993; Asmussen & Bonde-Petersen, 1974; Bobbert, Gerritsen, Litjens & van Soest, 1996; Cavagna, Dusman & Margaria, 1968; Enoka, 1988; Komi & Bosco, 1978; Walshe, Wilson & Ettema, 1998; Zajac, 1993).

The countermovement of a vertical jump is an example where an external force (e.g., gravity) lengthens the muscles of the leg. During the coordinated flexion of the hip, knee and ankle joints the muscles act eccentrically to lower the COM. The eccentric phase is followed by a brief transition period and finally a concentric (shortening) action follows. The combination of eccentric and concentric muscle actions is known as the Stretch-Shortening Cycle (SSC) (Komi, 1984; Komi & Nicol, 2000; Norman & Komi, 1979). The distinct sequence of SSC muscle function is shown in Figure 3.2: (A) prior to surface contact the muscle fascicle is activated (for rebounding or hopping tasks only); (B) on contact with the surface the activated muscle fascicle holds at its optimal length whilst the tendon is stretched; and (C) following the forceful stretch-reflex the tendon shortens, creating a catapult action releasing the stored elastic energy in the tendon that enhances performance (Komi, 2003).

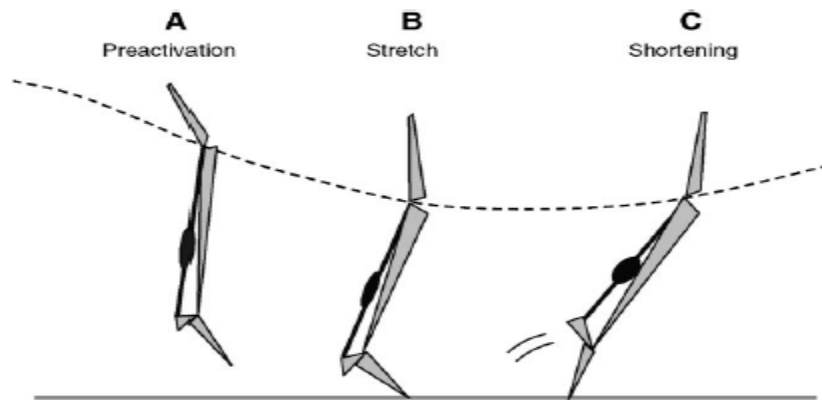


Figure 3.2: The sequence in muscle function during a stretch-shortening cycle (Adapted from Komi, 1984).

It is important to note that the agonist muscle group is activated before the stretch otherwise energy is not stored in the tendon structures. Furthermore, the time of the transitional phase can affect the amount of energy utilised from the elastic recoil during

the concentric phase. Therefore, the SSC is not only influenced by the force provided by the muscles but also by the elastic properties of tendon structures (Fukunaga, Kawakami, Muraoka & Kanehisa, 2002; Kubo, Kawakami & Fukunaga, 1999; Kurokawa, Fukunaga & Fukashiro, 2001).

A stretch reflex is a monosynaptic reflex arc that involves a rapid contraction of specific muscle fibres in response to a stretch (e.g., Komi, 2003). The stretch-reflex permits a rapid return of force during a short time period (< 0.2 s). The duration of the SSC during a countermovement jump is extended, therefore, the enhanced force production from the rapid stretch reflex is not optimally utilised when compared to more explosive movements (Komi, 2003; Kubo et al., 1999; Kurokawa et al., 2001). Compared to explosive rebounding, the elastic energy available to be utilised during a countermovement jump is low (Bencke, Damsgaard, Saekmose, Orgensen & Klausen, 2002). Therefore, the stretch-reflex contribution to force potentiation is less when jumping from a quiet stance compared to the contribution in more intense movements (e.g., hopping and rebounding). A prolonged ground contact time during a countermovement jump allows force to be developed actively, with the contribution of the stretch-reflex secondary (Feltner, Frachetti & Crisp, 1999; Komi, 2003). The explosiveness of the movement depends upon the duration of ground contact.

3.2.3. Amplitude

Aragón-Vargas and Gross (1997b) reported that the ‘best’ single predictor for jumping performance with no arm-swing was the normalised amplitude of the countermovement. The amplitude of the countermovement is best defined by the magnitude of flexion of the lower extremity joints. The relationship between countermovement amplitude and jump height has previously been reported (Bobbert & van Soest, 2001; Feltner et al., 1999; Vanrenterghem et al., 2004). Restricting the countermovement amplitude reduces the potential for storage of elastic energy and to a greater extent the time available to actively develop force in the leg extensor muscles (Anderson & Pandy, 1993; Feltner et al., 1999; Vanrenterghem et al., 2004).

In changing from sub-maximal intensity conditions of 25, 50 and 75%, to maximal jumps, increased amplitude was demonstrated by skilled jumpers ($n = 10$ male volleyball: age = 22.8 ± 3 years; stature = 184 ± 4 cm; mass = 77.9 ± 6.5 kg), through an increase in the hip joint amplitude (Vanrenterghem et al., 2004). The amplitude of the more distal knee and ankle joints remained unchanged. Work output followed a distal to proximal sequencing with ankle and knee joint contribution reaching maximum before the maximal jump condition at 50% and 75% conditions respectively. It was proposed that this sequencing permitted the body to minimise non-effective energy expenditure during sub-maximal jumping, due to the high rotational inertia of proximal segments when compared to the more distal segments (Vanrenterghem et al., 2004). Furthermore, the greater mass of the trunk passing through a greater range of motion increases jump

impulse and therefore VCOM at take-off (Bobbert & van Ingen Scheuen, 1988; Bobbert & van Zandwijk, 1999).

Generally, the depth of countermovement is not maximal (i.e., full flexion of hip, knee and ankles does not occur), but the amplitude reflects the physical qualities of the muscle–tendon complex (Bosco, Tihanyi, Komi, Fekete & Apor, 1982). The muscle–tendon complex is comprised of a passive and active component, with the tendon being part of the passive component and the level of compliance influencing the performance of jumping (Fukanaga, Kawakami, Muraoka & Kanehisa, 2002). The principal element of the active component is the fascicle, which includes the muscle fibres, and these generate force actively contributing to jump performance.

A significant correlation between jump height and muscle fibre composition ($r = 0.62$, $p < 0.05$) has been found (Bosco, Komi, Tihanyi, Fekete & Apor, 1983). Predominantly fast-twitch fibres located at the knee extensor muscles can store more energy and generate force more rapidly. In addition, individuals with predominately fast twitch fibres recover stored energy in high-speed countermovement jumps. Therefore, faster and smaller knee angular displacement would be observed when such individuals attempt maximal jumps. In comparison, for endurance trained individuals their fibre composition would be assumed to be predominantly slow twitch. In their case, duration and amplitude of the countermovement can be extended to optimise jump performance. Deeper amplitude of the countermovement increases knee flexion providing suitable conditions to permit equivalent recovery of stored elastic energy and force production. Although

theoretically plausible, it is difficult to endorse this research considering the assumptions and errors made during the assessment of fibre types. It is, however, worth noting that only 31% of jump performance can be explained by normalised amplitude of the countermovement (Aragón-Vargas & Gross, 1997b). Since 69% of the variance in this study was unexplained by the normalised countermovement, modifications to the countermovement to accommodate individual physical characteristics are therefore likely to provide the most suitable conditions for performance.

Composition of muscle fibres is not the sole physical factor that may determine the optimal countermovement amplitude, since the ability to recruit the motor units also contributes to performance. The importance of strength qualities in jump performance is supported by mathematical simulations that identified muscular strength to be the primary reason for increase in jump height and that fibre type was secondary (Pandy, 1990). Vanezis and Lees (2005) examined a homogenous group of competitive university soccer players (age = 20.5 ± 2.0 years) who were characterised on the basis of vertical jump as good or poor performers. From their findings, differences between the groups were due to the strength characteristics of the lower limb joints. In general, it was reported that work done, moments and power at the hip, knee and ankle joints, distinguished between good and poor jump performers. Technical differences between the groups were small. The jump movement showed minimal differences with some participants selecting to emphasise a ‘knee strategy’ at the expense of the hip or vice-versa. Those who demonstrated a ‘knee strategy’ demonstrated, larger than average values for work done, joint moments and power at the knee, with often lower than

average values of these parameters at the hip. Those with a 'hip strategy' demonstrated the reverse. For the study sample, an inverse relationship was found between knee and hip work done ($r = -0.604$, $p = 0.008$), and for peak hip and knee moment ($r = -0.488$, $p = 0.040$). This evidence further supports the notion that modified movement strategies are commonly employed to accommodate individual characteristics.

3.2.4. Neuromuscular Coordination

Training status, history and practice also influence motor unit activation and recovery of stored elastic energy rather than fibre type exclusively (Hakkinen, Komi & Kauhanen, 1986; Lattier, Millet, Maffiuletti, Babault & Lepers, 2003). Neuromuscular changes resulting from training (practice) can involve both intra-muscular coordination (as in fibre recruitment, rate coding and synchronisation) and inter-muscular coordination (as in activation of muscles in relation to other muscles i.e., antagonist activation and agonist inhibition).

Inter-muscular coordination is important in the execution of ballistic activities such as jumping, with the ability to inhibit antagonist activation being critical to the performance. If activation of the antagonist occurs during a ballistic movement, an increase in limb stiffness will be apparent, which is referred to as co-activation. From an equilibrium point control perspective, central control will pre-set thresholds of the tonic stretch-reflex on the muscle groups of both the antagonists and agonists that cross the specified joints

(Bizzi, Hogan, Mussa-Ivaldi & Giszter, 1992; Bullock & Contreras, 1993). For jumping, the pre-set thresholds for the initiation of the transition phase would be identified by the level of K_{leg} . Therefore, inter-muscular co-ordination determines the amplitude of the countermovement by controlling the level of flexion at the hip, knee and ankle joints. Typically during the learning of novel tasks inappropriate levels of co-activation are often observed, thereby reducing the ability of the individual to produce force (Raynor, 2001). Similarly, when movements are performed by a less skilled individual, co-activation can restrict the individual's joint range of motion. For example, excessive co-activation during jumping would hinder the transition phase from eccentric to concentric actions, both reducing the ability to utilise stored elastic energy, and hindering the ability to actively produce force by reducing the amplitude of the countermovement.

During human locomotion, leg stiffness and the angular velocity of joints are regulated by inter-muscular coordination. When co-activation of the antagonist and agonist muscle groups occurs, stiffness of the joint is high, limiting the angular velocity about the joint. The mechanisms that govern contractions of the agonist-antagonist muscle groups are: 1) centrally mediated reciprocal inhibition; 2) centrally mediated co-activation; 3) peripherally mediated reciprocal inhibition; and 4) peripherally mediated co-activation.

Previous observations suggest that in addition to the inter-muscular coordination, K_{leg} is dependent upon the fundamental properties of the musculoskeletal system, such as tendon compliance and reflex properties (He, Kram & McMahon, 1991; McMahon & Cheng, 1990). A mass-spring model has been used to represent the whole musculotendinous

stiffness of the lower limbs referred to as K_{leg} (Farley & Gonzalez, 1996). The lower extremities resemble the properties of a spring as peak force corresponds to the lowest point of the body's centre of mass during the countermovement. Theoretically, the ability to reverse joint actions of the lower limbs during a vertical jump when initiated from quiet standing requires transition from eccentric to concentric actions. For the movement to be efficient, control of the transition requires an appropriate level of K_{leg} . Otherwise, poor control would lead to inappropriate K_{leg} and hamper jump performance.

In tasks such as long jump, skilled adults have displayed task-specific levels of K_{leg} (Seyfarth, Friedrichs, Wank & Blickhan, 1999). When angle of take-off was changed the level of stiffness adjusted to optimise performance. The regulation of leg stiffness is dynamic and adjustments can be made to accommodate different compliance characteristics of surface types. For example, the total stiffness (i.e., human and surface system) was constant and leg stiffness was shown to increase by 3.6 times to accommodate for the more compliant surface in a study by Ferris & Farley (1997). These adjustments to leg stiffness give similar centre of mass mechanics during locomotion on different terrains (Ferris & Farley, 1997). In relation to the present study, changes in K_{leg} are not expected since the take-off angle is near 90° to the horizontal and the surface will remain unchanged (the forceplate).

The fundamental properties of the musculoskeletal system can be chronically altered by physical conditioning and practice. Leg stiffness measures have been shown to differentiate between those who participate in specific sports and their level of expertise

(Laffaye, Benoît & Durey, 2005). It is anticipated that due to lower levels of vigorous participation in physical activities, DCD children will have a lower expertise in jumping tasks and therefore display excessive levels of K_{leg} when compared to TD children. The higher levels of K_{leg} will reflect greater muscle co-activation caused by poor inter-muscular coordination.

3.2.5. Concentric Phase

Once the low point of the countermovement is reached, the upward movement or concentric phase is initiated. The concentric phase of jumping involves a stereotypical sequence of segmental extensions which starts at the hip, followed by the knee and finally the ankle. The explosive nature of this phase demands a pre-programmed response (Hatzitaki, Zisi, Kollias & Kioumourtzoglou, 2002). The precise timing (coordination) of the joint actions during the concentric phase is critical to jump performance (Bobbert & van Soest, 1994; Hudson, 1986; Luhtanen & Komi, 1978). The effective sequencing of proximal (hip) to distal (ankle) joints during the concentric phase (Bobbert & van Ingen Schenau, 1988) permits:

1. ground contact until the hip and knee joints are near full extension, which optimises the position of the COM at take-off (Bobbert & van Ingen Schenau, 1989, Bobbert & van Soest, 2001);

2. the mono- and bi-articular muscles to optimally interact and ensure ideal conditions for maximum force development at high joint angular velocities (Bobbert & van Soest, 2001; van Ingen Schenau, Bobbert & Rozendal, 1987);
3. the restrictions of both anatomical and geometrical constraints to be minimised (Bobbert & van Ingen Schenau, 1999); and
4. the amount of non-effective energy to be minimised at take-off (Bobbert & van Soest, 2001).

In order to maximise energy output, the mono-articular extensor muscles are required to release as much energy possible before take-off (Bobbert & van Ingen Schenau, 1988). Maximisation of this energy occurs when the vertical velocities of the upper body, upper leg, lower leg and feet peak in a proximal to distal sequence. In addition, the kinetic energy released must be optimally utilised for this transfer of energy to occur via the biarticular muscles. Consequently, segmental rotations during the propulsive phase produce an almost linear increase in the VCOM (Bobbert & van Ingen Schenau, 1988). In general, maximisation of energy output by the distal to proximal sequencing of joint actions during the concentric phase, has been observed throughout the literature for children older than six years of age (e.g., Jensen et al., 1994) and adults (e.g., Bobbert & van Soest, 2001).

Temporal and spatial coordination between the angular movements of the joints will determine the amount and shape of the vertical impulse (Oddsson, 1989). When the

combined head, arms and trunk (HAT) initiate extension, the large mass (approximately 70% of total body mass) produces a positive vertical acceleration that imposes a downward load on the knee extensors and ankle plantar flexors. The load imposed by the HAT delays the knee from initiating extension and especially the ankle plantar flexing. Consequently, a build up of tension (force) not possible under static conditions, occurs in the muscles around the knee and ankle joints. Following trunk extension, the muscle tension is released at the time of knee extension or plantar flexion of the ankle (Hudson, 1986; Pandy & Zajac, 1991).

Optimal control theory and the role of uniarticular muscles, has been examined by Pandy and Zajac (1991) using squat jumping. The authors observed that the uniarticular extensors (e.g., Gluteus Maximus) developed most of the propulsive energy, with the proximal extensors excited first. The biarticular leg muscles redistributed the segmental energy without producing much energy themselves. However, the Gastrocnemius was the exception. Rectus Femoris was an energy 'sink' (displaying eccentric activity). Of the biarticular muscles, hamstrings were excited first and the Gastrocnemius last. As a result of the redistribution of energy by the biarticular muscles, propulsion was prolonged allowing the full extension of the joints to occur near take-off. Thus, kinematically, an optimal solution exists for jumping, regardless of muscle properties (e.g., Ridderikhoff, Batelaan & Bobbert, 1999; Vanrenterghem et al., 2004; van Zandwijk, Bobbert & Munneke, 2000). Muscle properties are responsible, however, for jump performance (Aragón-Vargas & Gross 1997b).

The angular velocity of each joint of the lower limbs makes a strong contribution to the VCOM (Bobbert, 2001; van Ingen Schenau, 1989). Appropriate coordination maximises the contribution of each joint to the VCOM at take-off and is critical during vertical jumping for height. However, due to the geometric problem that is inherent in the transformation from a body with rotating segments to linear translation of the body, peak VCOM does not coincide with the instant of take-off (Bobbert & van Soest, 2001). With the orientation of each segment of the body approaching the vertical in preparation for take-off, the contribution of each segment's angular acceleration to linear velocity of the segment is diminished. Harman et al. (1990) found that the timing of peak VCOM was invariant for a group of physically active males ($n = 18$; age = 28.5 ± 6.9 years; stature 179.0 ± 5.4 cm; mass = 74.7 ± 7.7 kg) regardless of the jump employed. Peak VCOM occurred 0.030 ± 0.006 s before the instant of take-off for all four jumps used in the study. The jumps used were squat and countermovement jumps with and without arm-swing. During this time from peak VCOM to take-off, a loss in VCOM of approximately 6% occurred (e.g., arm-swing with countermovement jump trials, take-off VCOM = 2.61 ± 0.32 m.s⁻¹; peak VCOM = 2.77 ± 0.29 m.s⁻¹).

Coordination of the angular joint movements permits an efficient movement pattern which minimises the time period from peak VCOM to take-off. Minimising the time between peak VCOM and take-off will therefore optimise VCOM at take-off. During explosive movements a protection mechanism is initiated that decelerates joints approaching physical limits. The protective mechanism minimises the risk of soft tissue damage by co-activation of the muscle groups which reduces angular velocities (Jacobs et

al., 1996; Jaric, Ristanovic & Corcos, 1989; Jaric et al., 1999; Siff, 2000). Due to contribution of the individual joints to VCOM, decelerating the joints will in turn reduce take-off VCOM (Bobbert & van Ingen Schenau, 1988; Bobbert & van Soest, 2001). When the jumping movement is poorly orchestrated, premature vertical orientation of the body's segments or excessive co-activation may result in an early occurrence of peak VCOM. The early occurrence of peak VCOM results in a greater proportional loss in VCOM at take-off, thus, a less efficient performance.

Time elapsed from the peak VCOM to take-off was used by Falk et al. (1997) to examine neuromuscular coordination in young children during vertical jumping. The authors compared the jumping abilities of children aged 6-8 years who were born with low birth weight and prematurely to those of a group of controls. The time elapsed from peak VCOM and take-off was significantly longer in those children born prematurely (mean = 0.0411 ± 0.009 s) compared to the controls (0.0358 ± 0.0006 s). The difference was increased when the prematurely born group was subdivided into extremely, very and low birth weight groups. The extremely low birth weight subgroup displayed the longest time between peak VCOM and take-off (0.0502 ± 0.0012 s). The authors concluded this reflected a reduced coordinated effort, due to a deficit in agonist and antagonist coordination perhaps related to a deficit in cerebellar development.

A study by Haguenaer et al., (2005) found poor coordination in an elderly male group (mean age = 82.6 ± 7.8 yrs; stature = 1.67 ± 0.04 m; body mass = 63.3 ± 10.3 kg) during a squat jump when compared to a younger adult group (mean age = 22.1 ± 4.4 yrs; stature =

1.74 ± 0.05 m; body mass = 66.8 ± 7.2 kg). Figure 3.2 shows plots of the linear velocity of the HAT segment (combined head, arms and trunk), hip, knee and ankle joints. Clear differences between the groups are observed. These include lower and earlier occurrence of peak vertical linear velocities of the HAT, hip, knee and ankle joint in the elderly group. For the elderly, a more simultaneous coordination of the hip, knee and ankle was found. Consequently, the earlier occurrence of the HAT peak velocity found in the elderly group increased the ‘drop-off’ at take-off making the jump more inefficient. Unfortunately the authors did not use forceplate or report the timing of peak VCOM. This is shown by the difference between peak and take-off velocities on the Figure 3.3. It is, however, unclear from this study if the less explosive movement observed in the elderly group caused the earlier occurrence of the peak linear velocities in relation to take-off or if it was a coordination issue as previously proposed by Falk et al. (1997) from their study of young impaired children.

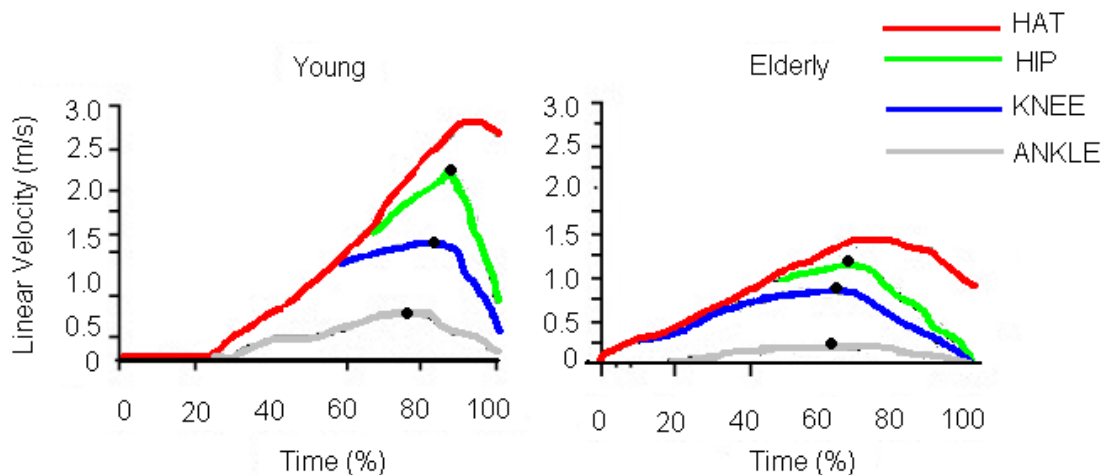


Figure 3.3: Comparison of vertical velocities of the combined head, arms and trunk (HAT), hip, knee and ankle throughout the concentric phase for one representative young (left) and elderly (right) participant (adapted from Haguenaer et al., 2005)

Balance and postural control are also important for a coordinated jumping movement. The sequencing from distal to proximal joint extensions ensures that dynamic balance is maintained. Generally, for balance to be maintained during the jumping movement, a horizontal position of the COM must remain within the base of support (Bobbert & van Ingen Schenau, 1988). To hold a position such as the initial stance, the COM must lie directly over the centre of pressure (COP) (located about 3.0 cm forward of the lateral Malleolus, depending on foot length). The coordination of the joint moments are adjusted so net acceleration is zero; that is, the vertical ground reaction force (VGRF) will be equal to the magnitude of the force of gravity and point vertically upward from the COP through the COM. From the bottom of the countermovement, increasing any joint torque will result in an upward movement of the COM. The particular activation pattern from proximal to distal ensures that balance is maintained. If upward movement (concentric phase) was initiated by activation of the knee extensors instead of the hip, an upward-backward acceleration of the COM would occur. If the upward movement was initiated by activation of the plantar flexors a forward displacement of the COP and a backward rotation of the COM would occur. Hip moment (relative to the knee), however, will cause the desired upward-forward acceleration of the COM. A coordinated movement pattern is therefore required, which helps maintain balance during vertical jumping.

3.2.6. Arm-Swing

The role of the arm-swing during jumping is not fully understood. A change in performance found by using arm-swing has been reported (Feltner et al., 1999; Harman et

al., 1990; Khalid et al., 1989; Lees et al., 2004; Oddsson, 1989; Payne et al., 1968; Shetty & Etnyre, 1989). Essentially, arm-swing enhances jump height compared to when it is restrained. Approximately 60% of the increased performance in a jump is the direct result of an increase in VCOM at take-off (Feltner et al., 1999; Lees et al., 2004). A 6-10% greater VCOM was found when the arms were used during vertical jumping (Harman et al., 1990; Luhtanen & Komi, 1978; Shetty & Etnyre, 1989). The remaining 40% of the improvement in jump height was accounted for by the elevation of the arms and hence COM position at take-off.

The VCOM at take-off is entirely due to the net vertical impulse (jump impulse) exerted by the adult during the propulsive phase (Harman et al., 1990). Interestingly, the duration of the propulsive phase has been reported to be quite stable, at around 0.32 s regardless of whether an arm-swing is used or not (Feltner et al., 1999; Harman et al., 1990; Oddson, 1989). With a constant time, differences in jump performance were attributed to the VGRF applied. Less consistency was found in the pilot to this study (Williams, Lythgo & Maschette, 2004), where the duration of the propulsive phase was significantly longer ($p < 0.01$) and showed greater variability for jumps involving no arm-swing compared to jumps with an arm-swing (Williams et al., 2004). It was concluded, that the difference found between jump protocols was evidence of learning and during the no arm-swing attempts, changes in impulse were not simply an increase in VGRF.

The timing of the arm-swing throughout the jump cycle appears to be consistent. High variability, however, of the arm orientation within the shoulder joint at specified instants

of the jump cycle have been observed (Williams et al., 2004). This high variability reflected the open-kinetic-chain nature of the arm movement, where the arms were free to move and were not in contact with the surface (Williams et al., 2004). The timing (coordination) of the arm motion can also affect the magnitude of the VGRF and enhance the propulsive and net impulses exerted on the jumper. In turn the larger jump impulse would result in an increased VCOM at take-off and augment jump height (Feltner et al., 1999).

Three theories have been put forward to explain the effect of arm-swing on VCOM at take-off. The ‘transmission of force’ theory (Payne et al., 1968) is one and this proposes that as the arms are accelerated upwards, a downward force is exerted through the body, instantly increasing the VGRF, which in turn leads to a greater impulse increasing the VCOM. Arm-swing can change the VGRF profile of the jumping movement throughout the movement. One source has reported that it superimposed one extra late peak onto the VGRF curve (Payne et al., 1968). It was this late extra peak in the VGRF curve immediately before take-off that differentiated the arm-swing and no arm-swing jumps. This enhancement of VGRF caused by arm-swing has not always been found. However, the ‘transmission of force’ explanation has been supported using experimental data indirectly (Harman et al., 1990) and directly by using simulation data (Dapena, 1999).

A second theory, explains the improvement in jump height as a result of arm-swing using the force-velocity relationship of muscle contraction (Feltner et al., 1999; Perrine & Edgerton, 1978). It is called the ‘joint augmentation theory’ and is based on the premise

that during the transition phase of the countermovement the musculature crossing the hips and knees are in the most advantageous position to exert VGRF. When transferring from the eccentric to concentric phase, the leg extensors are activated simultaneously with the upper body; the arm-swing imposes an initial vertical acceleration and exerts a downward force on the distal segments (Dapena & Chung, 1988; Harman et al., 1990; Kreighbaum & Barthels, 1981). The downward VGRF on the rest of the body prevents the segments from extending when the leg extensor muscles are activated. Extension of the upper legs is therefore delayed until the hips are weighted as the upper body acceleration decreases. This delay in extension of the legs as a result of arm-swing increases the time at which the muscles are held at their optimal lengths. In addition, the rate of contraction of the large leg extensor muscle groups (quadriceps and gluteals) is reduced to velocities at which they can exert more torque (angular force).

Finally, the 'pull' theory (Harman et al., 1990) suggests that towards the later part of the jump when the arms begin to decelerate, their high vertical velocity relative to the trunk enables them to 'pull' on the trunk, transferring energy from the arms to the rest of the body. Strength training for the shoulder flexor muscles has been associated with improved vertical jump performance (Narita & Anderson, 1992). Putting aside the associated limitations of the population tested (high school volleyball players), the findings may partly support the use of arm-swing to augment take-off velocity due to the 'pull' theory (Harman et al., 1990). During jumping with an arm-swing, the work done by the muscles of the shoulder and elbow together with the extra work done at the hip joint are used to build up energy at the arms. This in turn is used to initially work against the

body temporarily storing energy, to 'pull' on the body during which time the stored energy is released. The released stored energy increases the potential and kinetic energy of the arms at take-off.

The increase in work done at the hip in arm-swing jumping is a result of a greater trunk inclination which enables earlier and faster extension. Thus, more power is generated over a longer period. The greater work done at the hip is transferred to increase the energy of the arms and not the energy of the head-trunk-legs system (Lees et al., 2004). Once the arms have moved beyond the horizontal the vertical net joint force at the shoulder produces an upward force (pull) on the trunk which signals the rapid change. The increases in the knee and ankle joint angular velocities complement the already elevated joint torques, and as a result, an increased power output is observed (Lees et al., 2004).

A recent examination of each theory found that the increase in take-off velocity caused by the use of the arms was due to a complex series of events beginning at the start of the movement which manifest themselves towards the very end of the movement (Lees et al., 2004). The 'transmission of force theory' has been questioned, as previous work investigating arm-swing, found no additional peak in the VGRF curve (Miller, 1976). In contrast, arm-swing reduced the magnitude of peak VGRF but an overall increase in jump impulse was found. This suggests that force by time was increased over the concentric phase rather than simply an increase in magnitude occurring. More notably, net joint force at the shoulder was not instantly and accurately reflected in the VGRF

curve (Lees et al., 2004). Little similarity was found in either the shape or magnitude (Figure 3.4) of VGRF curves when arm-swing and no arm-swing jumps were compared. There was, however, some suggestion of a related but time delayed response from the application of a vertical force at the shoulder to its appearance in the VGRF. This could be explained by the force created by the arms serving to affect the working conditions of the muscles and through this, affecting the changes in the VGRF. Therefore the ‘transmission of force theory’ was not supported (Lees et al., 2004).

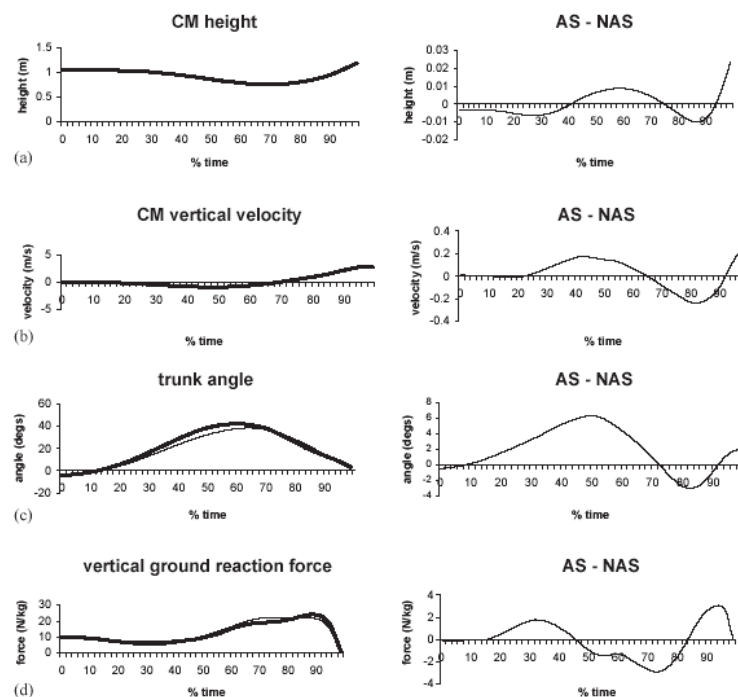


Figure 3.4: Averaged time-normalised graphs for arm-swing (AS, thick line) and no arm-swing (NAS, thin line) for: A) Centre of mass height; B) Centre of mass vertical velocity; C) Trunk angle; and D) Vertical ground reaction force. The graphs on the right-hand side represent the difference between the AS and NAS jumps (Adapted from Lees et al., 2004).

The ‘joint augmentation’ explanation has been criticised as it fails to recognise that the majority of the lower limb muscles cannot be classified simply as extensor or flexors since some are biarticular. Their activation will thus affect more than one joint (Bobbert

& van Ingen Schenau, 1988). Furthermore, although changes in lower extremity joint angular velocities, torques and powers related to arm-swing occur (Feltner et al., 1999; Lees et al., 2004), the “joint augmentation” theory predicts an increase in extensor torque during the period when the arms are accelerating upward. It is assumed that increased torque leads to an augmentation in performance through a faster joint angular velocity. Work by Feltner et al. (1999) suggests that during the first half of the ascent phase of an arm-swing jump where the muscle torque is greater, the joint velocity is lower which leads to a reduced joint power and reduced performance throughout this period (Feltner et al., 1999). Augmentation of joint torque is associated with the period during which muscles and tendons of the joint are storing energy and a greater joint torque would facilitate this. Therefore, augmentation of joint torque is associated with energy storage and it is the later return of this energy that enhances performance, rather than the direct application of increased torque (Lees et al., 2004).

All theories fail to exclusively explain the enhanced performance but the mechanisms appear to operate together. The energy built up by the arms came from the shoulders and elbow as well as from extra work done by the hip. This energy was used: 1) to increase kinetic energy and potential energy of the arms at take-off; 2) to store and release energy from the muscles and tendons around the hip, knee and ankle joints; and 3) to increase energy of the rest of the body through transmission of force directly to the body through the shoulder joint.

3.2.7. Muscular Strength

From the literature there is a well-established association between strength of the lower extremities and vertical jump performance (Fatouros et al., 2000; Genuario & Dolgener, 1980; Jaric et al., 1989; Newton., Kraemer & Hakkinen, 1999; Venable, Collins, O'Bryant, Denegar, Sedivec & Alon, 1991; Wisløff, Castagna, Helgerud, Jones & Hoff, 2004; Young & Biliby, 1993;). Strength (muscular strength) has been defined as the “ability to overcome or counteract external resistance by muscular effort and the ability to generate maximum maximum external force, (F_{mm})” (Zatsiorsky, 1995 p.230). The maximum maximum external force is in reference to the highest force that can be achieved under the most favourable conditions (Zatsiorsky, 1995). Indirectly, studies have shown a relationship between F_{mm} and jump performance with reported improvements of between 8 and 12% in vertical jump performance following a period of ‘strength training’ (Blattner & Noble, 1979; Brown, Mayhew & Boleach, 1986; Fatouros et al., 2000). Caution must be taken in view of these findings as the level of improvement may be influenced by the physical condition of participants’ pre-training (Lattier et al., 2003) and the mode employed. For example, improvements of 10% in vertical jump height following strength training using the squat exercise have been identified, whereas no improvements in jump performance were found using a leg press machine (Augustsson, Esko, Thomee & Svantesson, 1998). The superior results from the squat exercise, demonstrates the transfer of training due to specificity, where the squat training places greater demands on balance and control compared to the leg press. Similarly, as previously discussed from a simulation study, it has been suggested that jump height

would improve with increased muscle strength, but in order to take full advantage of these improvements, the countermovement amplitude would need to be adjusted (Bobbert & van Soest, 1994).

Support for changes in movement control caused by strength improvements of selected muscle groups has emerged from a study that has employed electromyostimulation (EMS) as a training mode (Maffiuletti, Dugnani, Folz, Di Pierno & Mauro, 2002). In this study, EMS was used to stimulate specific muscles. No significant improvements in jump performances were found after the four-week training protocol. Following the end of the EMS treatment however, a period of sports-specific training was performed and significant ($p < 0.05$) improvements were reported. This delay in enhancement of jump ability was attributed by the authors to the dependence of a pre-programmed muscle stimulation pattern. Therefore, time and practice may be required for the central nervous system to re-optimize the control to neuromuscular properties adding support for the view that other factors should be considered alongside strength or power as limiting factors (Aragón-Vargas & Gross, 1997a). Therefore, it would follow that rather than specifically concentrating on single joint strength measures alone, the ability to produce joint torques and powers during jumping seems important (Aragón-Vargas & Gross, 1997a; Vanezis & Lees, 2005). The findings of the Maffiuletti et al. (2000) study, however, are limited by the absence of a control group, as it allows for the possibility that training and playing itself may have been responsible for the performance improvements and not the EMS treatment.

The validity of using strength assessments to investigate relationships between strength measures and jump performance has been questioned. For example, during vertical jumps, the performance of the skeletal muscles of the ankle (plantarflexors) was found to be very different compared to their performance during uniarticular actions commonly used to assess strength (Bobbert & van Ingen Schenau, 1990). This comparison appears limited due to the relatively small contributions made by the ankle when compared to the knee and more importantly the hip (Hay, 1975). Hopkins, Schabert & Hawley, (2001) identified further limitations in the use of isokinetic assessments, suggesting that standardisation of positioning of the limbs is a source of error affecting the reliability and ultimately the validity of the measurements. The use of isometric conditions for the assessment of joint strength is an alternative sometimes used. Unfortunately skeletal muscles should be expected to generate greater torques than concentric actions, provided the isometric test is performed at the optimal joint angle (Lieber, 1992). Also, further discrepancies occur when assessing unilateral strength, as it has been shown to be greater than half the bilateral strength of leg muscles (van Soest, Roebroeck, Bobbert, Huijing & van Ingen Schenau, 1985). Finally, during multi-articular movements, net joint torque measures may include the action of the antagonist; when this occurs agonist torque is greater than the net torque indicates (Zajac & Gordon, 1989). This is a critical concern and a possible reason for a poor/moderate relationship between some strength tests and vertical jump performance. Strength is highly task specific and the transfer of ‘traditional’ strength assessments to evaluate fundamental movement performances is limited and should be made with caution (Siff, 2000).

As shown throughout the literature, the relationship between strength and jumping is unclear, and low correlations between the two variables (e.g., $r_{xy} = 0.35$ and $r_{xy} = 0.40$) have been reported (Considine & Sullivan, 1973; Misner et al., 1988 respectively). When jump height differences between groups are found, the general inference that muscular strength is responsible is erroneous without considering the kinematic and kinetic variables.

3.3. Vertical Jump as an Explosive Strength Test

Vertical jumping is a widely accepted measure of explosive leg strength or power (e.g., Aragón-Vargas, 2000; Bar-Or, 1996; Bosco & Gustafson, 1983; Davies & Young, 1984; Hatze, 1998; Harman, Rosenstein, Frykman, Rosenstein & Kraemer, 1991; Miller, 1988; Rodano & Squadrone, 2002; Sayers et al., 1999; Winter & MacLaren, 2001). Other established tests of lower limb explosive strength or power for children include, the standing broad jump, Wingate Anaerobic Cycle Test (WAnT), (Inbar, Bar-Or & Skinner, 1996), various isokinetic tests and the Margaria Stair-Run Test (Margaria, Aghemo & Rovelli, 1966).

The Wingate Anaerobic Cycle Test (WAnT) measures anaerobic power of the lower body by using maximal (all-out) pedalling on a stationary bike against resistance. An advantage of this testing protocol is that the body is supported which reduces balance demands. However, determining the optimal resistance for the assessment is particularly difficult since the response is highly individualised (Bar-Or, 1996). In addition, it is an

exhaustive test that requires some familiarity with strenuous vigorous exercise (Brown & Weir, 2001) and riding a bike ergometer.

Isokinetic tests allow strictly controlled testing of isolated movements of specified joint(s). The constraints of isokinetic testing include, actions (concentric only, eccentric only or combined), ranges of motion, and angular velocities. The lack of transfer of strength measures derived from isokinetic tests to movement in more natural settings is beyond the scope of this study and discussed elsewhere in detail (Bobbert & van Ingen Schenau, 1990; Brown & Weir, 2001; Hopkins et al., 2001). Isokinetic testing requires a number of considerations before its use, including, the variables to be measured (Peak Torque, Work, and Power), the isolation and stabilization of the body, the axis of motion, gravity compensation, the range of motion, standardisation of instructions and most importantly, the effect of practice. Since the dynamometer is novel to most participants, they may require several practice trials in order to achieve reliable torque tracings. It is recommended that subjects perform as many repetitions as needed to completely understand what is required during the testing or training process. Recommendations for the amount of practice required vary from as little as three repetitions for experienced resistance trained individuals, to as many as 15 for naive subjects (Brown & Weir, 2001). Practice required is a considerable concern for the reliability of such measures, especially when the sample is over 100 participants, all of whom have no experience with such exercises.

Both the WAnT and isokinetic tests involve reduced balance demands and movements which are not familiar. An alternative is the Margaria Stair-Run Test (Margaria, et al., 1966), which is a short-term explosive power test that requires stair climbing (running). The subject begins approximately six feet (two metres) from the first step and is instructed to run at top speed towards the stairs. Upon reaching the staircase, the subject should negotiate the steps two at a time until passing the second switch mat. The mats will correspond to the fourth and sixth steps taken. Power (P expressed in Watts) is then derived from the following Equation 3.1:

$$P = (W \times 9.8 \times D)/T \quad \text{.....Equation (3.1)}$$

Where: W = body mass of the subject (kg); 9.8 = acceleration of gravity in $\text{m}\cdot\text{s}^{-2}$; D = vertical height (m) travelled between switch mats one and two, and T = elapsed time (s) between switch mats one and two. Since the Margaria Stair- Run Test requires the participant to climb the stairs two at a time it may not lend itself to use with a young undersized population (Brown & Weir, 2001).

Vertical jumping has advantages over the three previous tests. Described as a fundamental movement skill, jumping is part of everyday physical activities for children and therefore a very natural and well practised movement (Gallahue & Ozmun, 2002). As a movement pattern, the co-ordination of jumping is very similar across individuals and motor ability demands are low. The stereotypical action of vertical jumping is purported to result from optimisation of neuromuscular control (Bobbert & van Ingen Schenau,

1988; Hatze, 1988). As a test, vertical jumping can easily be learnt, requiring little familiarisation compared to other assessments of leg strength qualities (Bar-Or, 1996). In addition, measures obtained from jumping tests give a performance outcome (jump height) but also, response measures that are highly reliable and relatively easily extracted from kinetic and kinematic data (e.g., Harman et al., 1990).

In field and laboratory environments, maximal vertical jumping has become a well established measure of lower limb explosive strength. Typically, explosive strength is defined as “the ability to exert maximal forces in minimal time” (Zatsiorsky, 1995 p225). This strength quality was originally assessed using the Sargent ‘jump and reach test’ (Sargent, 1921). This test, measures jump height from the differences in chalk marks made on the wall by the participants’ hand. Even today the assessment is still administered in the field at state institutes throughout Australia, as part of the physiological testing battery used to evaluate elite teams and athletes (Gore, 2000). Albeit the chalk has been replaced by a more sophisticated device called a “Vertec” the principle remains the same. The Vertec measures jump height by a series of finger like projections called vanes. The participant stands underneath with arm fully extended and the vanes are positioned so that the fingertip is aligned with the zero. On jumping vertically the participant attempts to displace as many vanes away from their starting position, resulting in a jump height to be recorded to the nearest one centimetre.

Recent technological advancements have seen the introduction of portable devices such as switch-mats (also known as contact mats). Switch-mats use a timing device that is

started once the participant has departed from the mat and stops on first contact (landing). Once the time in the air has been measured the jump height (Equation 3.2) can be calculated. The equation is based on the principle that the time the COM is falling is equal to one-half of the time in the air, which is only true if the participant takes off and lands with the body in the same position. This assumption, however, may lead to an overestimation in jump height (Dowling & Vamos, 1993) since the time down can be significantly longer than time up (average difference = 0.016 sec, $p < 0.001$), due to the participants landing in a crouched position (Aragón-Vargos, 2000).

$$JumpHeight = g \cdot \left(\frac{tair}{2} \right)^2 \cdot 2^{-1} \quad \text{.....Equation (3.2)}$$

Where: g = is acceleration due to gravity (9.81 m·s⁻²) and tair is the air time (flight time).

Jump height attained from ‘jump and reach’ tests and switch-mats can be used to estimate peak power (Fox & Mathews, 1974; Harman et al., 1991; Sayers et al., 1999). Yet, the accuracy of prediction is highly dependent upon the type of protocol performed (Sayers et al., 1999) and the heterogeneity of the population used to develop the equation (Aragón-Vargas, 2000; Sayers et al., 1999). However, within the limitations, in general, under field conditions, the prediction of power from vertical jump height has been widely accepted. The displacement or jump height obtained appears to be the best measure of performance. For jump and reach tests, jump height reached are measured directly, thus eliminating any source of error in prediction of a power component (Hopkins et al., 2001).

Cheaper more compact technology now allows laboratory-based methods to be used in the field. These include forceplates (500-1000Hz) and digital video cameras (50Hz). The higher sampling rate of the forceplate system compared to that of a video camera however, allows a more accurate estimate of jump height (van Praagh & Doré, 2002). The vertical velocity of the centre of mass at take-off calculated this way has been shown to contain less error than when calculated from video derived data (Lamb & Stothart, 1978). Therefore, forceplate derived data, which includes impulse and velocity is more appropriate and offers a greater validity when using vertical jumping measures.

Construct validity has generally been assumed for vertical jumping when assessing explosive strength (Bosco & Gustafson, 1983). Jumping is part of everyday activity for children (Gallahue & Ozmun, 2002), therefore the test procedures require little familiarisation compared to other assessments of explosive leg strength (Bar-Or, 1996). Vertical jump testing while using a countermovement therefore is expected to be stable and display high reliability.

Statistically, the reliability of vertical jump tests ($r_{xy} = 0.87$ and above) using young adult participants has been well established (Aragón-Vargas, 2000; Ashley & Weiss 1994; Bar-Or, 1996; Bosco & Viitasalo 1982; Davies & Young, 1984; Goodwin, Koorts, Mack, Mai, Morrissey & Hooper, 1999; Harman et al., 1990; Miller, 1988; Young, MacDonald, Heggen & Fitzpatrick, 1997; Young, MacDonald & Flowers, 2001). Test reliability ($r_{xy} = 0.93$; $CV = 2.4\%$) of jump height obtained from a switch-mat was found to be high and stable (Moir, Button, Glaister & Stone, 2004). This study was conducted, over a three-week period where 10 active male participants (25.3 ± 6.6 years; 76.2 ± 9.0 kg; and 1.75

$\pm 0.08\text{m}$) performed three vertical jumps as part of a battery of assessments, on five separate occasions. The best jump performance was kept for analysis during each of the five occasions. From the observations, it was concluded that jumping vertically was a well learnt skill for active young males and due to the high reliability and stability of performance across the trials, no need for familiarisation is necessary (Moir et al., 2004). Furthermore, Arteaga, Dorado, Chavarren and Calbet (2000) reported small variability in jump height for both squat ($\text{CV} = 5.4\%$) and countermovement jumps ($\text{CV} = 6.3\%$) with no arm-swing. These measures of reliability were obtained from six test sessions over a 12 week period, suggesting that there is little sign of learning over time for both of these test protocols.

In addition to reliability, test validity has also been examined using four different methods to derive jump height for the same performance. These methods involved kinematic data (60Hz), forceplate data (300Hz), air time and a combined kinematic and forceplate data to determine jump height (Aragón-Vargas, 2000). Reliability coefficients (r_{xy}) ranged from 0.970 to 0.994 and the standard error of measurement for jump height ranged between 12.1 and 27.8 mm. Although, all methods were reliable, caution was advised because the jump height obtained for the same performance changed across methods. No test validity was therefore established and the author recommended that comparisons across studies which used different methods to calculate jump height would be meaningless.

Jump height, take-off velocity and other variables derived from forceplate data have been reported to provide excellent test-retest reliability using four different jumps when performed by physically active males ($n = 18$; age = 28.5 ± 6.9 years; stature 179.0 ± 5.4 cm; mass = 74.7 ± 7.7 kg) (Harman et al., 1990). For the countermovement jump with arm-swing Cronbach's α reliability scores ranged from 0.958 to 0.996. The reliability scores for individual variables are listed in Table 3.1.

Table 3.1: Test-retest reliability of vertical jump measures with arm-swing (Harman et al., 1990)

Variable	Cronbach's α
Peak negative COM displacement	0.958
Peak positive COM displacement	0.988
Positive Impulse	0.989
Negative Impulse	0.962
Net Impulse	0.996
Peak VCOM	0.994
Take-off VCOM	0.994
Minimum VGRF	0.899
Peak VGRF	0.983
Peak positive Power	0.989
Peak negative power	0.970

Specific test-retest reliability data using forceplate assessment have not been reported for a paediatric population (van Praagh & Doré, 2002). However, for jump and reach tests reliability appears to be less than that for the adult population (Bosco & Gustafson, 1983). Cureton (1945) for example, reported $r_{xy} = 0.78$, for a sample of 74 young boys between 7 and 13 years. Nonetheless, vertical jumping offers many advantages as a tool for assessment of children. Characteristically, vertical jumping is a whole body task that involves a countermovement with arm-swing. This movement pattern is most likely to be part of the child's play, sporting or physical education experience (Cousins & Smyth, 2003). The extent to which this movement is employed will be dependent on a number of

factors such as; how active the child is, what opportunities there are available and level of motor proficiency. As an everyday activity and a fundamental motor skill the vertical jump assessment may be considered ecologically valid. As the influence of learning is unlikely, systematic error may be minimised and extensive practice of the test may not be required. This supports the use of vertical jumping with arm-swing for the assessment of movement competence in children.

3.4. Typical Development of Vertical Jumping

Only once a child has acquired the ability to walk and run, does the movement task of jumping emerge. Generally, by the second birthday, a tendency to jump has been observed, although, it is not until the ages of three or four years that a coordinated effort is apparent (Clark et al., 1989; Jensen et al, 1994; Phillips et al., 1985). A stable pattern becomes evident around the age of six years (Gallahue & Ozmun, 2002) and co-ordination of vertical jumping from quiet stance is very similar across individuals (Vanrenterghem et al., 2004).

For children, jumping is an integral part of movements that are used every day in physical activity. Vertical jumping, therefore, has been identified as a fundamental movement skill (Gallahue & Ozmun, 2002). It is important to consider that a ‘fundamental movement skill’ entails only the basic elements of a particular movement; it does not require a high degree of skill or include the individual’s style or personal peculiarities in performance. It does imply developing acceptable levels of proficiency and efficient body mechanics in

a wide variety of movement situations. The absence of participation in physical activity, for whatever reason, will limit a child's exposure to fundamental movements, restricting the opportunity to learn, and develop.

Traditional age-stage theories of motor development in fundamental motor skills propose that motor ability develops in a progressive series of stages, characterised by periods of relative consistency in motor patterns interspersed with periods of rapid change (Gallahue & Ozmun, 2002). Table 3.2 shows the proposed sequence of stages for vertical jumping development (Myers et al., 1977; cited by Gallahue & Ozmun, 2002).

Table 3.2: Summary of Developmental stages of Vertical Jumping (adapted from Gallahue & Ozmun, 2002).

1st. Initial stage	
	1. Inconsistent preparatory crouch 2. Difficulty in taking off with both feet 3. Poor body extension on takeoff 4. Little or no head lift 5. Arms not coordinated with the trunk and leg action 6. Little height achieved
2nd. Elementary stage	
	1. Knee flexion exceeds 90-degree angle on preparatory crouch 2. Exaggerated forward lean during crouch 3. Two-foot take off 4. Entire body does not fully extend during flight phase 5. Arms attempt to aid in flight (but often unequally) and balance 6. Noticeable horizontal displacement on landing
3rd. Mature stage	
	1. Preparatory crouch with knee flexion from 60 to 90 degrees 2. Forceful extension at hips, knees, and ankles 3. Simultaneous coordinated upward arm lift 4. Upward head tilt with eyes focused on target 5. Full body extension 6. Elevation of reaching arm by shoulder girdle tilt combined with downward thrust of non-reaching arm at peak of flight 7. Controlled landing very close to point of takeoff
Developmental Difficulties	
	A. Failure to get airborne B. Failure to take off with both feet simultaneously C. Failure to crouch at about a 90-degree angle D. Failure to extend body, legs, and arms forcefully E. Poor coordination of leg and arm actions F. Swinging of arms backward or to the side for balance G. Failure to lead with eyes and head

The evidence supporting age-stage theories (e.g., Robertson, 1978) has been criticised because it has been based on qualitative evaluation of movement sequences rather than theoretical frameworks supported by objective data derived from kinematic and kinetic measures (Clark & Phillips, 1985; Harrison & Bowker, 2000; Hellebrandt, Ratrick, Glassow & Carns, 1961; Larkin & Hoare, 1991; McCaskill & Wellman, 1938; Poe, 1976).

More sensitive measures made possible through improved technology have enabled researchers to gather evidence to refine theories for the development of motor competence. One such alternative approach is Dynamical systems theory, which describes changes that occur when learning new movements and how control emerges. Within this framework, the degrees of freedom ‘problem’, based on Bernstein’s (1967) work, identifies that there are many different ways in which each joint and segment can move. Therefore, when performing a task involving multiple segments, the number of options and the complexity associated with controlling them increases as well. Bernstein proposed that the ‘solution’ to the ‘degrees of freedom problem’, was to organise these segments and joints into synergies or coordinative structures that work together (Haehl, Varaxis & Ulrich, 2000).

Bernstein viewed learning of a new skill as a process in which central control progressively manages the large number of degrees of freedom. His model for motor learning exhibits three stages (p, 107-109):

1. Initially reducing (freezing) the number of degrees of freedom at the periphery to a minimum;
2. Gradual lifting (releasing) of all restrictions on the degrees of freedom, that is, to the incorporation in movement coordination of all possible degrees of freedom; and
3. Finally, utilising and exploiting the reactive phenomena that arise in movement control.

Evidence for Bernstein's model of motor learning has been discussed in the broader context and elaborated on elsewhere (Newell & Vaillancourt, 2001). In the case of jumping, evidence supporting Bernstein's model has been presented using kinematic technology. Such evidence includes the increase in joint ranges of motion at the periphery with age (Jensen et al., 1994; Wang, Lin & Huang, 2003). In the latter study, six year-old children were found to restrict the amplitude of the countermovement through freezing of the distal joints, when compared with 18 year-olds. Significantly smaller ranges of motion at the ankle and knee joints were found in the younger group (Table 3.3). At the proximal (hip) joint, the range of motion was not significantly different between groups (Wang et al., 2003).

Table 3.3: Hip, Knee and ankle ranges of motion (ROM) during the crouch (eccentric) and push-off (concentric) phases of the jump (adapted from Wang et al., 2003).

Group	Hip ROM (°)		Knee ROM (°)		Ankle ROM (°)	
	6 year-olds	18 year-olds	6 year-olds	18 year-olds	6 year-olds	18 year-olds
Crouch Phase	50.9±12.2	63.6±12.26	50.7±10.3*	65.4±6.2	17.8±4.2*	26.3±1.8
Push Phase	68.7±9.5	76.4±11.2	72.4±7.3*	83.8±7.5	55.1±6.4*	68.1±8.0

* indicates significant difference between 6 year-old and 18 year-old groups ($p < 0.05$).

Jensen et al. (1994) showed similar findings when kinematic differences were found at distal joints and segments between an adult group, a group of children with high take-off (HTO) and a group of children with low take-off angles (LTO). Presented in Tables 3.4 and 3.5, the adult group had mean knee and ankle angles at take-off, significantly greater than both groups of children (HTO and LTO). Interestingly, no difference across groups was found for the hip angle at take-off. At take-off, the distal body segments (foot and shank) show differences between the adults and children (HTO and LTO). A significantly more vertical shank was found for the adult and HTO groups when compared to the LTO group, whilst the trunk also showed a difference between adults and the two groups of children, but failed to reach significance. These findings suggest that control of the distal joints is acquired later in development, as shown in the adult (18 years old) groups, where the degrees of freedom are ‘released’. Both studies, however, involved cross-sectional designs and therefore any developmental inference is limited.

Table 3.4: Mean and standard deviations of joint angles (in degrees) for adult and children's high (HTO) and low (LTO) take-off angle groups (from Jensen et al. 1994).

<i>Event</i>	<i>Group</i>	<i>Ankle</i>	<i>Knee</i>	<i>Hip</i>
Start of movement (VGRF _{min})	Adult	112.4 ± 9.7	143.3 ± 14.2	135.7 ± 28.9
	HTO _c	105.2 ± 7.3	152.7 ± 8.1	146.2 ± 11.4
	LTO _c	99.6 ± 1.7 ^a	141.3 ± 11.7	142.3 ± 20.6
Low point (VGRF _{peak})	Adult	92.1 ± 7.0 ^c	93.2 ± 11.4	110.6 ± 17.1
	HTO _c	91.6 ± 8.7 ^c	113.7 ± 15.6	114.1 ± 17.8
	LTO _c	82.1 ± 6.4 ^{a, b}	95.9 ± 19.3	94.6 ± 16.5
Take-off	Adult	145.8 ± 8.5 ^{b, c}	169.5 ± 2.2 ^{b, c}	170.6 ± 5.1
	HTO _c	134.7 ± 6.8 ^a	162.8 ± 5.7 ^{a, c}	166.1 ± 9.8
	LTO _c	128.5 ± 7.2 ^a	149.0 ± 7.5 ^{a, b}	170.7 ± 7.4

VGRF_{min} = minimum vertical ground reaction force;

VGRF_{peak} = peak vertical ground reaction force

^a Group significantly ($p < 0.05$) differs from adults

^b Group significantly ($p < 0.05$) differs from HTO_c

^c Group significantly ($p < 0.05$) differs from LTO_c

Table 3.5: Mean and standard deviations of segmental angles (in degrees) for adult and children's high (HTO) and low (LTO) take-off angle groups (adapted from Jensen et al., 1994).

<i>Event</i>	<i>Group</i>	<i>Foot</i>	<i>Shank</i>	<i>Thigh</i>	<i>Trunk</i>
VGRF_{min}	Adult	140.1 ± 6.4	72.5 ± 5.5	109.3 ± 10.6	65.0 ± 19.2
	HTO _c	153.1 ± 8.0 ^a	78.2 ± 4.6 ^{a, c}	105.2 ± 5.5	72.1 ± 6.5
	LTO _c	152.9 ± 3.7 ^a	72.5 ± 3.8 ^b	111.2 ± 9.7	73.5 ± 11.3
Take-off	Adult	113.9 ± 8.7	79.7 ± 1.5 ^c	90.1 ± 2.1	80.6 ± 3.8
	HTO _c	120.0 ± 7.8 ^c	74.6 ± 4.5 ^c	91.9 ± 4.3	77.9 ± 7.2
	LTO _c	108.3 ± 7.0 ^b	56.8 ± 6.8 ^{a, b}	97.8 ± 3.9	78.4 ± 5.8

VGRF_{min} = minimum vertical ground reaction force;

^a Group significantly ($p < 0.05$) differs from adults

^b Group significantly ($p < 0.05$) differs from HTO_c

^c Group significantly ($p < 0.05$) differs from LTO_c

The final stage of Bernstein's (1967) learning framework suggests that the structure of a movement is organised to effectively exploit the passive forces arising from the reactive interactions of limb and torso body segments (Newell & Vaillancourt, 2001). This means when conditions characterise a certain situation, a specific stable pattern of behaviour (limb movement) emerges (Magill, 2007). The emergence of a stable jumping pattern is evidenced in the timing of the joint reversals and peak velocity joint reversals (Clark et

al, 1989; Jensen et al, 1994; Phillips et al., 1985). Jumping is characterised by a proximal to distal order of joint reversals during the concentric phase, i.e., from a flexed position at low point, the upward movement is initiated by hip extension, which is followed by the extension of the knee and then ankle. The timing of peak extension velocities generally follows the same sequence, ensuring efficient jumps with minimal loss of VCOM at take-off. This sequence represents the neuromuscular system's general strategy for propulsion, which once learnt is stable, regardless of age and different conditioning (Clark et al., 1989).

Mechanically, it is advantageous to accelerate the system for as long as possible, increasing each joint's velocity to the last possible moment before takeoff (Bobbett & van Soest, 2001). Because all the joints' velocities peak near takeoff, delays between peaks are necessarily minimal. Similar results for the timing of peak extension velocities have been reported for adults performing the vertical jump (Bobbett & Ingen Schenau, 1988; Bobbett & van Soest, 2001; Clark et al., 1989; Hudson, 1986; Jensen & Phillips, 1991) and the standing long jump (Phillips et al., 1985).

Utilisation of the SSC and effective K_{leg} are two indications that the passive forces within the muscle-tendon-complex are effectively exploited. Children as young as 6 years were found to take advantage of the SSC during vertical jumping (Harrison & Gaffney, 2001). However, the pre-stretch augmentation (Equation 3.3) expressed as a CV (Equation 3.4) displayed marked differences in variability when compared to an adult group (20 year-

olds). Children (CV = 187.8%) displayed almost double that of the adults (CV = 88.3%). The reduction found in the variability of the adult group may be a general characteristic of motor development and learning. Furthermore, evidence of a lack in development or learning was found when the variation across the three trials for each subject was analysed (Harrison & Gaffney, 2001). The existence of a large variability in the pre-stretch augmentation suggests that the coordination in the children was sub-optimal and not well learnt (Bobbert et al., 1996; Harrison & Bowker, 2001; Williams et al., 2004).

$$\text{Pre-stretch augmentation} = (V_{\text{TO(CMJ)}} - V_{\text{TO(SJ)}} / V_{\text{TO(SJ)}}) \times 100 \quad \text{..... Equation (3.3)}$$

$$\text{Coefficient of Variation (CV)} = (\text{Standard deviation} / \text{Mean}) \times 100 \quad \text{..... Equation (3.4)}$$

Where $V_{\text{TO(CMJ)}}$ is take-off velocity for a countermovement jump and $V_{\text{TO(SJ)}}$ is take-off velocity for a Squat jump

Investigations of K_{leg} during vertical jumping are limited and to date, only one study has compared a group of 6 year olds with a group of 18 year olds (Wang et al., 2003). Wang et al. reported that when K_{leg} was normalised for body weight, it was significantly less ($p < 0.05$) in the 6 year old group compared to 18 year old children. This would seem to contradict Bernstein's final stage of learning as more compliant joints (less stiff) have been associated with more efficient running and rebounding (e.g., Farley & Gonzalez, 1996; Ferris & Farley, 1997; Komi, 2003). Less K_{leg} allows passive forces within the muscle-tendon unit to be exploited permitting greater energy return. In addition, if the degrees of freedom are frozen at the distal joints during learning, greater K_{leg} would be

expected due to increased muscle co-activation in the young children prohibiting joint flexion. Therefore, the technique used by Wang et al. to normalise K_{leg} may be inappropriate and an alternative analysis should have been explored (McMahon & Cheng, 1990).

Practice is required for shifts in behaviour to occur (Haehl et al., 2000). Progression to this efficient jumping movement pattern will, therefore, not simply occur given time. The rate of achievement relies on factors within the task, the individual and environmental factors over time. The rate of shift in behaviour and the progress towards achievement of an efficient jumping movement pattern are generally expected to vary in children, for a variety of reasons. The timing will be determined by the quality and quantity of instruction, encouragement and opportunity to practice; when these factors are absent the differences in progression become evident (Gallahue & Ozmun, 2002).

Jensen et al. (1994) suggest the coordination pattern for jumping is established early, around the age of two years. Generally, what is lacking in children who are unskilled is the command over parameters that tune and refine the performance. They suggested that control parameters include: 1) strength; 2) balance; 3) perception; and 4) motivation. Poor control of these parameters has been found in children with unstable jumping patterns. During the standing long jump in children aged from three to seven years of age, developmental differences in take off characteristics such as horizontal displacement, take-off angle and the use of upper extremities have been found (Phillips et al., 1985). In some cases, the less developed children performed similar jumps, unable to distinguish

between a vertical and standing broad jump (Clark et al., 1989). It is likely that loss of distal control can explain forward movement during the countermovement of the vertical jumps. This forward displacement can lead to a significant horizontal displacement, giving the impression of a standing broad jump.

3.4.1. Age Related Trends in Jump Height and Other Outcome Measures

Typical development coincides with improved jump height and from the age of 4 to 30 years detectable improvements have been observed (Bosco & Komi, 1980; Haguenaer, et al., 2005). This improvement in jump performance can be explained by physiological differences (van Praagh & Doré, 2002) rather than changes in the movement pattern (Aragón-Vargas & Gross, 1997a; 1997b). Longitudinal research has shown that the rate of annual progress with age in jump height is highly variable when assessed by field measurements (Beunen et al, 1988; Philippaerts et al., 2006). The rate of improvement per year for vertical jump height ranged from 1.5-5.1 cm·year⁻¹ (Table 3.6) and was found to be dependent upon the timing of the assessment in relation to the period of rapid growth known as peak height velocity (Philippaerts et al., 2006). Therefore, the greatest rate of increase in vertical jump height was found at the time of peak height velocity. Peak height velocity resembles the greatest change in stature between assessments. In Tables 3.6 and 3.7, the time of peak height velocity was given zero months. Longitudinal data for each participant were then aligned using peak height velocity (zero). This method of aligning longitudinal data accounts for the large intra-group variation in growth

(developmental) rates for children and is explained in detail by Beunen and Malina (1988). At the commencement of the study, a group of young pre-adolescent male soccer players' physical characteristics were assessed and monitored throughout their development. Peak height velocity was attained at a mean age of 13.8 years. The data generated during each 6 month period were reported from 12 months pre- through to 12 months post- peak height velocity.

Table 3.6: Mean growth velocities and weight data of soccer players aligned on individual peak height velocity (PHV) (adapted from Philippaerts et al., 2006).

Variables		Months from PHV								
		-24	-18	-12	-6	0	6	12	18	24
Height (cm · year ⁻¹)	mean	5.7	5.7	6.7	8.2	9.7	7.6	5.6	4.5	3.5
	<i>s</i>	1.1	0.9	1.7	1.3	1.5	1.2	2.4	1.9	1.6
	<i>n</i>	9	9	33	33	33	33	33	17	17
Weight (kg · year ⁻¹)	mean	2.7	3.2	5.0	6.6	8.4	7.1	6.4	5.7	4.1
	<i>s</i>	0.8	1.6	2.1	2.0	3.0	1.9	3.1	2.3	3.1
	<i>n</i>	4	4	21	21	21	21	21	14	14

Note: Mean age at PHV = 13.8 years.

Table 3.7: Changes in performance in physical fitness tests by years of soccer players aligned on peak height velocity (PHV) (adapted from Philippaerts et al., 2006).

Motor tests		Months from PHV				
		-12	-6	0	6	12
FBA (attempts · year ⁻¹)	mean	0.1	1.2	2.5	1.2	0.1
	<i>n</i>	12	12	12	12	10
PLT (s · year ⁻¹)	mean	0.7	0.7	0.8	0.6	0.5
	<i>n</i>	9	9	9	9	8
SAR (cm · year ⁻¹)	mean	1.0	0.6	-0.1	1.3	2.7
	<i>n</i>	9	9	8	8	8
SLJ (cm · year ⁻¹)	mean	6.3	8.4	10.5	10.1	10.1
	<i>n</i>	10	10	10	10	10
VTJ (cm · year ⁻¹)	mean	1.5	3.3	5.1	3.8	3.3
	<i>n</i>	12	12	12	12	12
SUP (sit-ups · year ⁻¹)	mean	0.4	1.5	2.7	1.6	0.8
	<i>n</i>	11	11	11	11	10
BAH (s · year ⁻¹)	mean	-2.9	2.2	7.6	6.1	5.2
	<i>n</i>	17	17	16	16	16
SHR (s · year ⁻¹)	mean	0.4	0.9	1.6	0.7	0.1
	<i>n</i>	14	14	14	14	12
SSPRINT (s · year ⁻¹)	mean	0.1	0.4	0.9	0.5	0.2
	<i>n</i>	12	12	10	10	9
DASH (s · year ⁻¹)	mean	-0.6	-0.1	0.4	0.3	0.2
	<i>n</i>	8	8	8	8	7
ESHR (min · year ⁻¹)	mean	0.1	0.6	1.5	0.7	0.0
	<i>n</i>	12	12	11	11	9
STEMPO (s · year ⁻¹)	mean	1.4	2.1	3.5	2.9	2.6
	<i>n</i>	15	15	14	15	14

Note: Number of participants (*n*) can vary between tests at successive half-year intervals before and after age at PHV. Boys whose maximal velocity points were located at V1 or V7 (or V5 for those who were examined four times) were excluded because it is likely that the real maximal velocity was located before V1 or after V7 (or V5).

Abbreviations: FBA = flamingo balance; PLT = plate tapping; SAR = sit and reach; SLJ = standing long jump; VTJ = vertical jump; SUP = sit-ups; BAH = bent arm hang; SHR = 10 × 5 m shuttle run; SPRINT = 5 × 10 m shuttle sprint; DASH = 30 m dash; ESHR = endurance shuttle run; STEMPO = anaerobic capacity as measured by a shuttle run.

For the individuals that participated in the study, the mean rate of improvement for jump height of 1.5 cm·year⁻¹ was observed 12 months prior to the time of peak height velocity. Peak height velocity coincided with the greatest improvement rate of 5.1 cm·year⁻¹.

An earlier longitudinal study tracked vertical jump changes through development using similar methods. The study involved a larger, more heterogenous sample of 444 young boys who were not specifically trained (Beunen et al., 1988). In contrast to the soccer study, the greatest improvements of almost 5 cm·year⁻¹ were found six months following

peak height velocity. However, the rate of improvement in vertical jump height was similar two years before peak height velocity (approximately $2 \text{ cm} \cdot \text{year}^{-1}$). The reduced magnitude found in the soccer study (Philippaerts et al., 2006) may be due to the higher baseline data recorded due to the training or due to a smaller sample size.

Jump impulse and take-off velocity follow similar age-trends to jump performance. Significant differences ($p < 0.001$) were reported between children and adult groups for jump impulse and take-off velocity (Davies & Young, 1984.) Further, experimental data derived from forceplate assessments for children in the literature are displayed in Appendix 1. Consistent with vertical jump height, peak power normalised for body mass has shown age related trends. A summary of published normative and relevant experimental data for field tests (e.g., Baumgartner & Jackson, 1991) and laboratory based data for vertical jumping, (e.g., Ferretti et al., 1994) are provided in Tables A1 and A2 in Appendix 1.

Normalised peak power from countermovement jumps was found to be significantly ($p < 0.010$) lower in children aged 6 years (mean $\approx 30 \pm 4 \text{ W} \cdot \text{kg}^{-1}$) when compared to adults aged 23 years (mean $\approx 52 \pm 8 \text{ W} \cdot \text{kg}^{-1}$) (Harrison & Gaffney, 2001). Significant differences ($p < 0.01$) for normalised peak power were also observed between groups when squats jumps were performed. Adults produced a greater normalised power output (mean $\approx 47 \pm 8 \text{ W} \cdot \text{kg}^{-1}$) compared to the children (mean $\approx 28 \pm 5 \text{ W} \cdot \text{kg}^{-1}$). However, children displayed a greater ($p < 0.05$) normalised power output for the countermovement jump when compared to the squat jump whereas no differences were found between

jumps for normalised peak power for the adult group. The authors concluded that the children failed to produce similar peak power output in the squat jump when compared to the countermovement jump due to the squat jump being a novel task which was unmastered (Harrison & Gaffney, 2001).

Similar differences in normalised peak power output between groups of adult and children have been found (Ferretti et al., 1994). Using a squat jump, children (aged 8-13 years) were compared to three sedentary adult groups (aged 20-35 years; 35-50 years; and over 50 years) and an adult athletic group (aged 26 ± 3 years). Normalised peak power outputs were greatest in the athletic group ($55.3 \pm 5.2 \text{ W}\cdot\text{kg}^{-1}$), followed by the 20-30 year-old sedentary group ($43.1 \pm 5.8 \text{ W}\cdot\text{kg}^{-1}$), the 35-50 year-old sedentary group ($39.5 \pm 4.9 \text{ W}\cdot\text{kg}^{-1}$), the over 50 year-old group ($34.8 \pm 5.6 \text{ W}\cdot\text{kg}^{-1}$) with the children recording the lowest mean normalised peak power output ($31.6 \pm 8.4 \text{ W}\cdot\text{kg}^{-1}$). From the findings of Ferretti et al. (1994) it was shown that differences between adults and children could not be accounted for by physical activity alone, however, for adults normalised power output can be affected by age-trend and training. Normalised peak power output has been reported to be significantly related to other variables derived from forceplate data such as: jump height ($r = 0.92$); average power output ($r = 0.97$); and jump impulse ($r = 0.99$) (Davies & Young, 1984). Forceplate data permits peak power output, average power output and jump impulse to be accurately assessed (Harman et al., 1990; Sayers et al., 1999). Normalised measures are necessary as body mass is of critical importance to power output and other force derived variables (Docherty, 1996).

However, differences between adults and children can not be explained by mass alone (Davies & Young, 1984).

Beyond the age of 11 years significant gender differences in jump height are expected for vertical jumping, when boys jump higher (Butterfield, Lehnhard, Lee & Coladarci, 2004; Thomas & French, 1985; Malina et al., 2004). Thomas and French, from their meta-analysis inferred that no pre-pubertal differences between genders, for vertical jump, were found (Mean ES = 0.18). Post-puberty, however, gender differences were evident (Mean ES = 1.50) favouring the boys. The gender difference post-puberty, was suggested to be related to both biological development and environmental factors. For boys, jump performance increases steadily to the age of 17, while the girls' performance reaches a plateau after the age of 11 years (Amateur Athletic Union, 1993; Butterfield, Lehnhard, Lee & Coladarci, 2004). Growth and especially leg length have been shown to be a positive contributor to the improvements in jump height (Butterfield et al., 2004).

Balance was reported to follow a similar pattern to vertical jumping where differences emerged between genders only post-puberty. Tasks where a small to moderate (ES = 0.20 - 0.50) difference were found between genders pre-puberty included: running (dash); shuttle run; sit-ups; catching and surprisingly long jump. These gender differences pre-puberty were explained by environmental factors; such as opportunities and encouragement to practice (Halverson, Robertson & Langendorfer, 1982) rather than biological differences. The authors noted the unexpected differences found in vertical jump and long jump, but did not attempt to offer an explanation. A convenient and

speculative response would be that the balance demands are far greater when landing from a long jump and not well practised until an older age.

Having reviewed the DCD and jumping literature, the conceptual framework for this study will now be presented, in chapter four.

CHAPTER IV

THE CONCEPTUAL FRAMEWORK FOR THE STUDY

Fitness test data have suggested that DCD children perform poorly on explosive leg strength tasks including vertical jumping (Hammond & Dickson, 1994). When jump performance for a group of DCD children ($n = 17$) was compared to normative data the median jump height was found to be equivalent to the 25th percentile, with individual scores ranging from 1st – 90th percentile for their age (6 and 7 years). However, thorough comparisons of the jump performance of TD and DCD children have not been reported. Vertical jumping was selected for this investigation because it potentially offers a useful starting point for a more general study of critical coordination differences between TD and DCD children. This claim is based on the known characteristics of the vertical jump, which include:

- 1) it is a fundamental movement skill (Gallahue & Ozmun, 2002); and
- 2) one optimal solution exists, which provides the most favourable conditions for the neuromuscular system to coordinate the movement (Bobbert & van Inge Schenau, 1988);

The conceptual framework for the enquiry is structured at four levels, providing the basis for the hypotheses that have been developed (Figure 4.1). The first level of the framework is jump height, which is the basic performance measure.

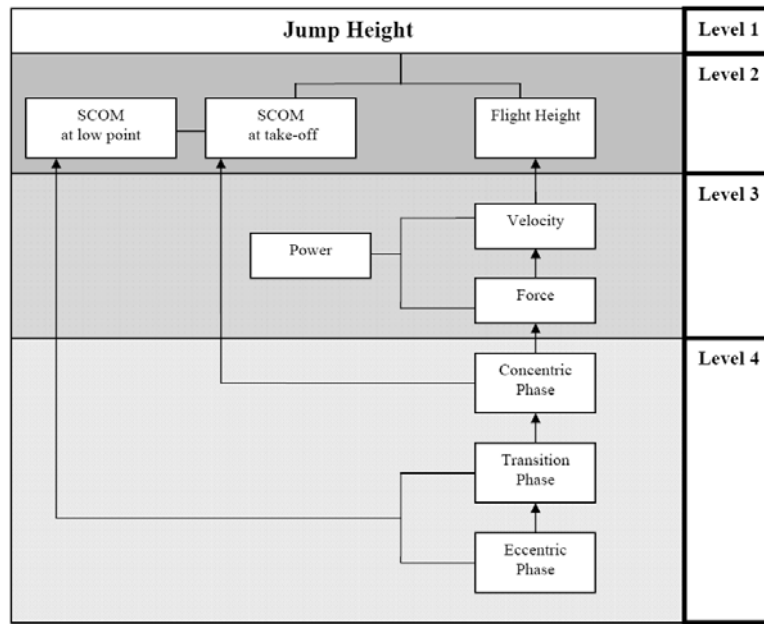


Figure 4.1: The four levels of the conceptual framework for enquiry.

The second level includes measures derived from the SCOM data, which describe the jumping movement from a whole body viewpoint and include:

- the SCOM at low point, which describes the depth of the countermovement;
- the SCOM at take-off, which describes the general extension of the limbs at take-off; and
- the flight height, which describes the SCOM following take-off as a result of the countermovement.

Flight height at the second level, is in turn determined by the force and velocity variables, which comprise level three (e.g., Feltner et al., 1999). In addition, power variables are included at the third level as they describe the interaction between force and velocity.

Level four includes variables specific to the countermovement, which relate to both the SCOM variables at level two and the force, power and velocity variables included at level three (e.g., Enoka, 1988). The eccentric and transition phases underpin the SCOM at low point, whereas the concentric phase is the determinant of the SCOM at take-off and flight height.

A further elaboration is that the variables at the four levels shown in the conceptual framework (Figure 4.1) are underpinned by sub-levels derived from kinetic and kinematic data. These sub-levels permit the higher level variables identified to be examined more thoroughly. For example, the whole body is represented by the SCOM, which can in turn, be explained by the joint and segmental angles at that instant. This relationship is identified in Figures 4.2, 4.3, 4.4 and 4.4, which show each level in isolation with the relevant sub-levels. All variables are defined in the methods section.

Hypothesis 1: Jump height will be significantly different between TD and DCD groups.

From previous jump data (Hammond & Dickson, 1994), it was predicted that children identified with DCD will jump lower when compared to TD children.

Hypothesis 2: The SCOM during the jump movement will be significantly different between TD and DCD groups.

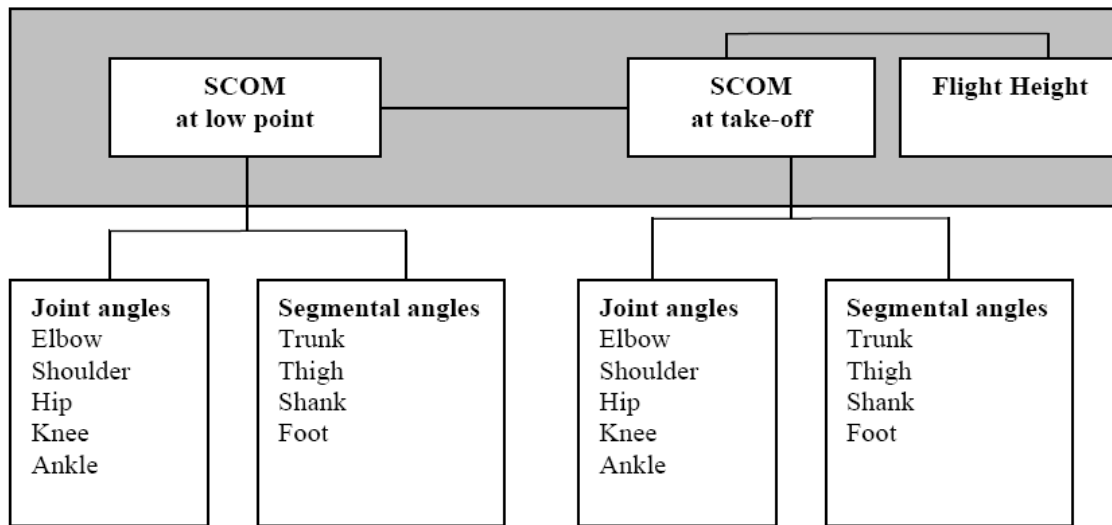


Figure 4.2: Elaboration of level two variables: Displacement of centre of mass variables and their sub-levels

Hypothesis two is based on the premise that overall, the SCOM throughout the jumping cycle will be different between the groups. The three key level two variables of the jump cycle are identified in Figure 4.2. All help explain jump performance. The depth of the low point is expected to be a contributing factor as it allows time and angular distance for the participant to develop force. In examining the sub-level variables, of particular relevance to this investigation, a restriction of the distal joints (knee and ankle) at the low point has previously been found (e.g., Wang et al., 2003), which can be caused by increased muscle co-activation resulting from learning or coordination error (e.g., Raynor, 2001).

A restricted low point has also been reported in children identified with DCD when compared to TD children during maximal standing broad (horizontal) jumps (Deconinck et al., 2005). No significant group differences for kinematic variables were, however,

found when sub-maximal (60-70%) attempts were analysed. At the joint and segment sub-levels, group differences in countermovement were due to a pronounced hip flexion in the TD group. The more efficient use of the trunk segment, together with the significantly larger horizontal displacement of the COM before take-off, were suggested to be the main factors underlying the better maximal jumping performance by the TD group. It was concluded that the problems in broad jumping of children identified with DCD did not lie in the coordination of muscle activation, but rather in the control of the trunk and dynamic equilibrium (Deconinck et al., 2005). Constraining hip flexion may reflect a sub-optimal coping strategy by the DCD children; preventing a challenge to balance control and a risk of falling, but thereby reducing performance. Therefore, it is anticipated that the countermovement will be restricted in the DCD group, yet, how this is achieved at the joint and segmental sub-level remains unclear. Balance issues will be identified by a lack of joint flexion at the low point compared to the TD group. Based on developmental research (e.g., Jensen et al., 1994), if the movement pattern is not established, either smaller joint and segmental angles will be apparent in the DCD group in an attempt to freeze the degrees of freedom of the distal end, or the resultant joint flexion will be excessive, representing collapsing or falling forward where balance is lost.

At take-off, SCOM is also predicted to differentiate between TD and DCD groups. From previous qualitative observations, DCD children do not reach full body extension at take-off (Larkin & Hoare, 1991). Therefore, SCOM at take-off will be lower in the DCD group. At the sub-level, from the kinematic analysis at take-off, differences between groups at the distal joints are expected, based on previous developmental jumping

research (e.g., Jensen et al., 1994). Poor balance and postural control in the DCD group would predict greater flexion at the joints and the segments would be more horizontally orientated compared to the TD group at take-off. Such joint and segmental angles are consistent with the reported observation of falling forward at the instant of take-off, resulting in lower SCOM at take-off in the DCD group (e.g., Jensen et al., 1994). A lower SCOM at take-off may exclusively explain the previously lower jump height reported for DCD groups. This is because the baseline measure used to standardise jump height was based on the assumption that all participants are extended at take-off (Hammond & Dickson, 1994). Therefore, for this study, in order to remove the effect of SCOM at take-off on jump height, flight height in the DCD group will also be compared to the TD group.

Hypothesis 3a: Velocity variables will be significantly different between TD and DCD groups.

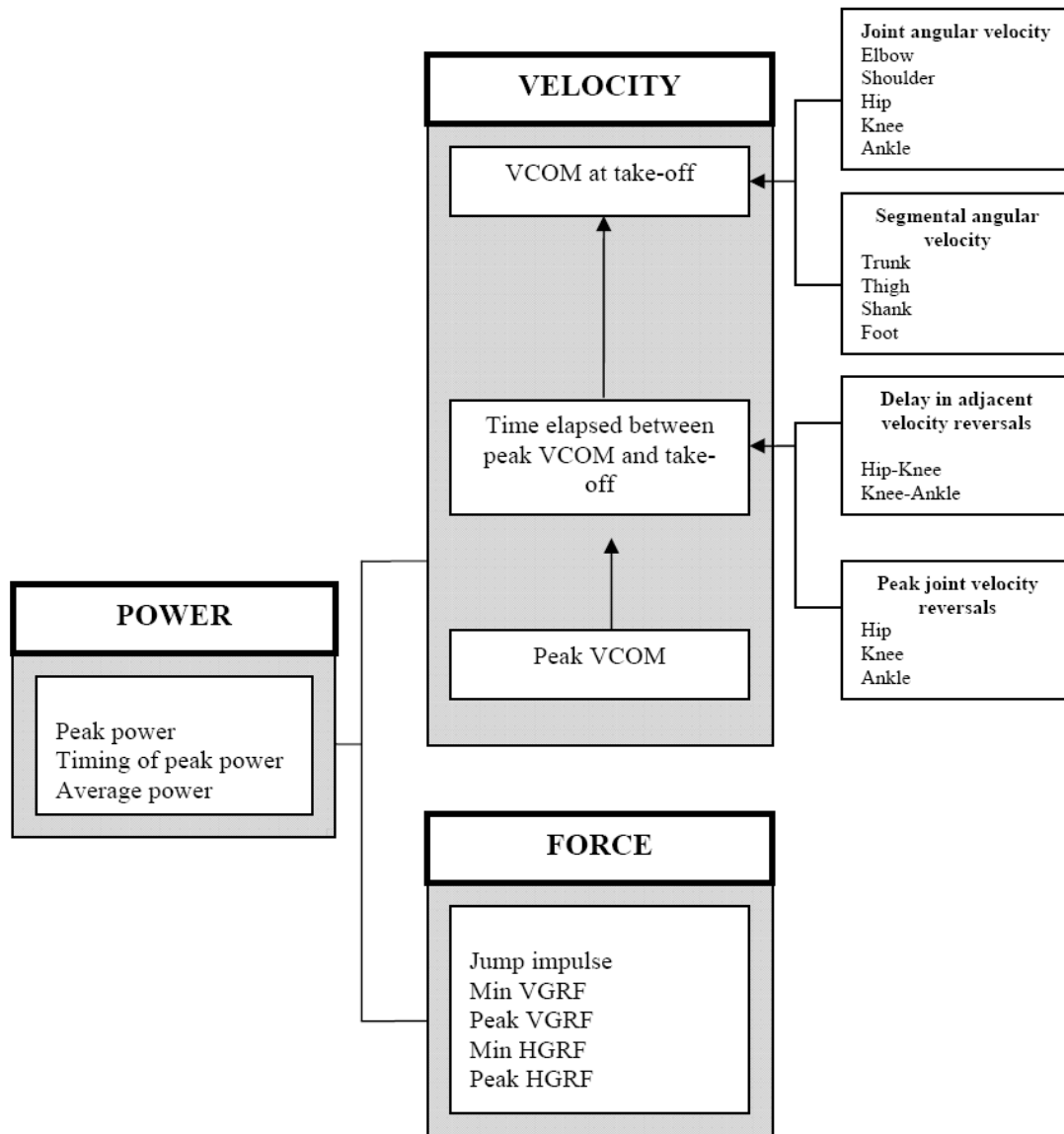


Figure 4.3: Elaboration of level three variables: Force, power and velocity variables and their sub-levels.

As previously reviewed in chapter three, children aged 6-8 years who were motor impaired as a result of being born prematurely with low birth weight, displayed lower mean peak VCOM ($1.51 \pm 0.24 \text{ m}\cdot\text{s}^{-1}$) when compared to a control group ($1.78 \pm 0.30 \text{ m}\cdot\text{s}^{-1}$) (Falk et al., 1997). Thus, lower peak VCOM will be a reflection of poorer jump performance. Of particular relevance to the current investigation, the time elapsed from

peak VCOM to take-off was significantly longer in those children born prematurely (mean = 0.0411 ± 0.009 s), compared to the controls (0.0358 ± 0.0006 s). This difference was increased when the prematurely born group was subdivided into extremely low, very low and low birth weight groups. The extremely low birth weight subgroup displayed the longest time between peak VCOM and take-off (0.0502 ± 0.0012 s). The authors concluded that this reflected impaired coordination, due to a deficit in cerebellar development, or at least a deficit in agonist and antagonist coordination. Falk et al.'s study, however, was limited. Children were aged between 6-8 years; it is not known if the timing of peak VCOM will be affected at older ages. Based on work reported using an elderly adult sample (Haguenauer et al., 2005; refer to Figure 3.4), it is possible that the earlier peak VCOM found by Falk et al. may be caused by a lack of explosive movement, which resulted in a VCOM curve without a distinct peak leading up to take-off (plateaux).

Furthermore, in both of the aforementioned studies, the angular velocity contributions of each joint and segment to VCOM at take-off were not investigated. The delay in adjacent joint velocity reversals and timing of peak joint reversals are important measures when investigating coordination, as they characterise a stable and well established jumping pattern (Clark et al., 1989; Jensen et al., 1994). It is therefore expected that group differences at these sub-level variables may be observed if coordination issues are exhibited by the DCD group.

Hypothesis 3b: Force and power variables will be significantly different between TD and DCD groups.

At level three, velocity and force variables determine height achieved following take-off (flight height). Power, the product of force and velocity is also included at level three. Although, it has been suggested that for the countermovement jump power output does not directly relate to jump height (Winter & MacLaren, 2001), power measures can give additional information as to the explosive nature of the movement performed (Zatsiorsky, 1995).

Force development (VGRF) especially that produced during the concentric phase of the jump (jump impulse), is a central determinant of jump height (e.g., Winter & MacLaren, 2001). Although VGRF variables attained from a maximal vertical jump have not been reported in the DCD literature, significantly lower levels of maximum force (torque) have been reported for children identified with DCD, compared to their peers, when assessed using single joint isokinetics (Raynor, 2001). In Raynor's study, the DCD group displayed a decreased peak extensor torque compared to the TD group, the two groups differed at all speeds at the six year olds, but at nine years, the groups only differed at the higher velocities only (165 and 210 deg·s⁻¹). This finding from Raynor's study highlights the importance of using high speed or explosive movements, such as maximal vertical jumping, to identify differences between TD and DCD groups at ages above 9 years (Deconinck, DeClercq, van Coster, Salvetsbergh & Lenoir, 2005; Raynor, 2001). It also suggests that differences in maximum VGRF will be lower in DCD groups.

Differences in force production between TD and DCD groups have been associated with difficulties at the muscular level, exhibited by DCD children. These difficulties include: increased motor times (or electromechanical delay) (Raynor, 1998); ineffective muscular organisation during postural control (Williams et al., 1983), such as a lack of anticipatory stabilisation of the trunk musculature (Johnston et al., 2002); and excessive levels of co-activation of the agonist and antagonist muscle groups caused by a less developed level of muscular organisation (Raynor, 2001).

Poor balance and posture control associated with DCD result in collapsing of joints and this in turn will be reflected in greater minimum VGRF measures. In addition, greater Horizontal Ground Reaction Forces (HGRF) magnitudes in both negative and positive directions for the DCD group will provide further evidence for balance and posture issues, as a result of larger anterior and posterior departures of the COM from the base of support.

A greater decrease in power output by DCD children at greater angular velocities has also been reported when compared to their peers (Raynor, 2001). These differences were proposed to be an outcome of either lower activity levels or fibre type differences (Raynor, 2001). This proposed association, however, was circumstantial and the level of activity or muscle composition was not assessed.

Short-term power performance by children with DCD has also been measured directly using the Wingate anaerobic test (WAnT) (O' Beirne et al., 1994), and indirectly using performance measures from hopping, jumping and sprinting (Larkin, Hoare, Phillips & Smyth, 1988; O' Beirne et al., 1994; Raynor, 1998). All studies demonstrated differences from groups of TD children. Generally, inefficient movement patterns were used to explain the differences displayed between the groups, although a mechanical analysis of such movements was not reported.

O'Beirne et al. (1994) reported that the DCD group displayed significantly lower levels ($p < 0.05$) of power output from the WAnT than controls, once the power data were normalised for body mass. Normalised peak power was $25.46 \pm 5.39 \text{ W}\cdot\text{kg}^{-1}$ for the DCD group compared to $30.80 \pm 5.19 \text{ W}\cdot\text{kg}^{-1}$ for the control group. Notably, for all the children, differences between age and gender groups were removed when power outputs were normalised for mass. Normalisation of power data from maximal vertical jumps are expected to yield lower outputs in the DCD group when compared to the TD group.

The studies mentioned above did not, however, report the timing of peak power, which may explain how well the TD and DCD groups coordinate the vertical jump. A well coordinated jumping movement will be organised so that peak power occurs close to the instant at take-off. If coordination difficulties exist, however, the instant of peak power will occur earlier in the jump cycle and further away from the take-off.

Hypothesis 4: The countermovement at the eccentric, transition and concentric phases will be significantly different between TD and DCD groups.

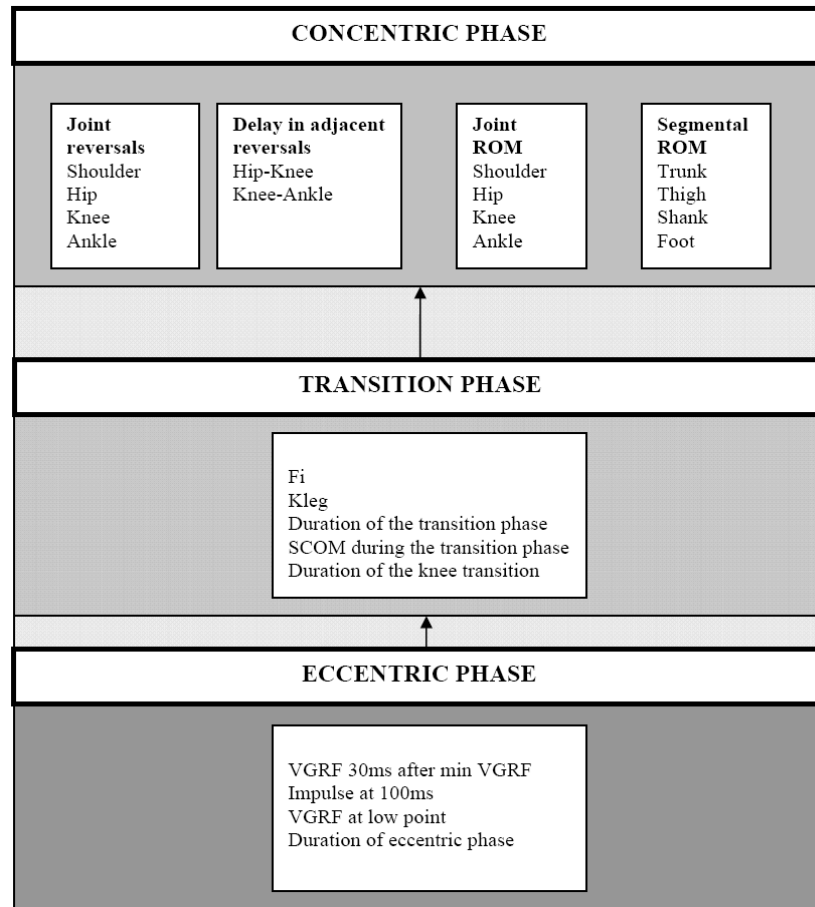


Figure 4.4: Elaboration of level four variables: The sub-levels of the three phases of the countermovement.

The eccentric phase begins once a movement downwards is commenced from the standing position. It terminates at the instant where instantaneous power first becomes positive. During this phase of the countermovement, measures of eccentric loading can be obtained derived from kinetic data. They include the duration of the eccentric phase, VGRF 30 ms after minimum VGRF and impulse at 100 ms after minimum VGRF. Collapsing of joints, caused by poor control or a lack of strength will be indicated by

greater values for these variables of eccentric loading. In addition, from the mass spring model, the VGRF at low point gives the force produced at the instant in time where the mass spring is maximally compressed (Farley & Gonzalez, 1996). At low point the VGRF would be greater in the TD group who are anticipated to be both stronger and better coordinated when compared to those identified with DCD. To date, measures attained from the eccentric phase have not been reported in the DCD literature, however, it is anticipated that these variables will be sufficiently sensitive to differentiate between groups if differences in how the body is initially released are exhibited.

The transition from eccentric to concentric joint actions during a multi-joint task, such as vertical jumping, has not been investigated in children identified with DCD. A simple uni-joint isokinetic task, however, was found to be a particular problem for children identified with DCD (Raynor, 2001). During the transition phase, excessive co-activation of the muscle groups that cross the knee, to the detriment of force and power output were found. In particular, the older children could cope with slow (sub-maximal) velocities, but only demonstrated difficulties when higher task velocities were attempted (Raynor, 2001). For jumping, excessive co-activation at the time of transition between eccentric and concentric joint actions will cause an increase in K_{leg} , which may restrict the countermovement amplitude. Such restrictions and observed stiffness have been reported, but not quantified in DCD children when landing following a jump (Larkin & Hoare, 1991; Larkin et al., 1988). Therefore, for the DCD group, the variables that describe the transition from eccentric to concentric phases (F_i , K_{leg} , duration of the transition phase

and duration of the knee transition) are expected to be significantly different. These variables are explained in more detail in the method section of this study.

Moreover, if the DCD group's eccentric and transition phases are different as anticipated, the subsequent concentric phase will also be different to the detriment of performance (jump height). A restricted low point will reduce the range of motion of the joints and segments, reducing the potential to actively produce VGRF. Furthermore, there is a coordination issue, this could be identified by group differences in the joint reversals and the delay in adjacent joint reversals.

Hypothesis 5: Group differences for jump measures will increase at older ages.

Children generally become more efficient and refine their muscular activation patterns through various movement experiences and interactions with the environment (Basmajian & De Luca, 1985). Furthermore, between the ages of five and eight years has been identified as an important period in the development of strength and motor performance (Malina et al., 2004). This period also coincides with the establishment of the coordinated jumping pattern in TD children (Gallahue & Ozmun, 2002).

During this important stage for potential improvement (Bar-Or & Rowland, 2004), physical activity avoidance by those identified with DCD can lead to a 'vicious' cycle of hypoactivity. Inefficient muscular activation patterns of children with DCD may be both a cause of physical activity avoidance but also a consequence of their often limited

movement experiences (Bouffald et al., 1996). Physical activity avoidance can therefore severely disrupt further movement development. As a result, differences in motor performance between TD children, and those identified with DCD, become increasingly evident during this period, and the risk of physical activity avoidance also increases.

It is noteworthy that there will be exceptions and some children identified with DCD will still out perform some of those in a TD group. The DCD children who are the exceptions and score within normal ranges may explain why longitudinal research shows that some children with DCD ‘grow out of it’ over time (e.g., Visser et al., 1998). With no obvious differences for certain motor performances compared to their TD peers, these children can continue to participate in physical activity without the fear of being singled out.

However, for the others who score low in all motor performances, this presents a problem that is exacerbated by avoidance of physical activities (Raynor, 2001). For those identified with DCD who choose to participate, sub-maximal coping strategies may be adopted and atypical movement patterns for movements such as jumping may appear (Hay et al., 2004; Larkin & Parkin, 1998).

An expanding gap in movement efficiency between DCD and TD children at older age groups has been shown in two previous studies (O’ Beirne et al., 1994; Raynor, 2001), and is the expectation for this study. O’Beirne et al. found that from seven to nine years, differences between the fatigue index for DCD and controls became larger. The fatigue index was derived from the drop in power output from the start to the end of the all out test (where a large fatigue index would suggest an inefficient movement pattern or lack of

physical fitness). Group difference became more evident because the TD group's fatigue index improved at the older ages, whereas that of the DCD group decline. Raynor's study reported similarity in peak force production between a 9 year old DCD group and a 6 year old control group. The trends with age in the TD group supports Bernstein's (1967) notion of a learning framework, where movement efficiency is achieved by exploiting the reactive phenomena. In contrast, the lack of change and possible decline with age found in the DCD group supports the 'vicious' cycle notion (e.g., Bar-Or & Rowland, 2004), and the compounding impact DCD can have on the developing child (e.g., Parker & Larkin, 2003).

In summary, this investigation seeks to confirm previous finding concerning the difference in vertical jump performance between DCD and TD children. It then uses kinematic and kinetic analysis of the jump action to go beyond differences in performance to achieve a better understanding and explanation of performance differences between TD and DCD children aged between 5 and 12 years. Whereas previous work has been limited to measures such as jump height and qualitative observations (e.g., Hammond & Dickson, 1994; Larkin & Hoare, 1991; Raynor, 1998), this study approaches the problem by using a more detailed biomechanical analysis of jump performance. The findings from this study will therefore contribute to the DCD literature through the kinematic and kinetic analysis, and add to current understanding of coordination and control differences between TD and DCD children at different ages.

CHAPTER V

METHOD

5.1. Participants

Following approval by the Australian Catholic University's Human Research Ethics Committee, Department of Education and Training Victoria (reference number SOS001127) and the Catholic Education Office (reference number GE99/0009), letters were sent to 20 principals of primary schools in Melbourne, Australia (refer to Appendix 3 and 4). One school with children from what may be considered a predominantly middle socioeconomic status catchment area (largely industrial based employment, median weekly household income of \$856; Victorian Electoral Commission, 2001) agreed to take part in the present study. Its willingness to take part was based on its ability to accommodate the logistical demands of the study and a general concern for its pupils. Following confirmation by the school's principal, letters of consent, with an information sheet (Appendix 3) were sent to the participants. All forms were completed and returned to the school before the commencement of the study. It was clearly stated in the consent forms that at any time, either the parent or the child could terminate involvement in the study. All the children who had returned the forms and were present at school on the days of testing were given the opportunity to participate. In total, 165 children participated and completed all assessments.

The M-ABC was used to identify those children who were significantly motor impaired, that is, they scored below the 15th percentile of the age-expected norm (DSM-IV criterion A). Through discussion with the teachers, criterion C and D were met as none of the children from the sample used for the analysis were known to have learning and physical health problems. However, Criterion B for DCD was not directly evaluated. This would have required completion of the more detailed part of the M-ABC parent/guardian survey known as the 'checklist'. Completion of the checklist requires a parent/guardian's participation and their interpretation of their child's ability to perform daily activities. For similar sized research studies it is common for this part of the assessment not to be completed and criterion B not to be included in the screening process (Hay et al., 2004; Visser, 2003). Therefore, for the present study, those who met the criterion (excluding criterion B) were described as children identified with DCD from the M-ABC.

Sixty-two children were identified with DCD, which represented 37.6% of the total sample of 165 participants who had completed the M-ABC. The children identified with DCD were then matched using age, stature and mass with those who had scored above the 15th percentile on the M-ABC. In the case of two or more possible matches for the DCD child, the TD child with the higher percentile score was selected. Gender was not used to match participants.

Age, stature and mass were selected as the criteria for matching as they were considered as the most important factors that can contribute to differences in explosive power movements within the population (e.g., Bosco & Gustafson, 1983). The criteria were

applied using age first (within 10%), then stature (within 10%) and body mass (within 10%).

5.1.1. Physical Characteristics

To examine differences resulting from ageing and physical growth, children identified with DCD and the matching participants from the TD sample were grouped by the age-bands defined by the M-ABC. Age band 1 included 5 and 6 year olds; Age band 2 included 7 and 8 year olds; Age band 3, included 9 and 10 year olds; and Age band 4 included 11 and 12 year olds. Eight groups were therefore used in the analysis, as shown in Table 5.1. That there were no significant differences between groups for age, stature and mass was confirmed by using independent t-tests for all age band comparisons.

Table 5.1: Group characteristics for age, stature and mass.

		DCD	TD	DCD	TD	DCD	TD	DCD	TD
		<i>Age-band 1</i>	<i>Age-band 1</i>	<i>Age-band 2</i>	<i>Age-band 2</i>	<i>Age-band 3</i>	<i>Age-band 3</i>	<i>Age-band 4</i>	<i>Age-band 4</i>
Gender	Gender	8m:9F	8m:8F	9m:8F	12m:9F	8m:9F	7m:7F	7m:4F	4m:7F
	N	17	16	17	21	17	14	11	11
Age (years)	Mean	6.182	6.286	7.975	8.062	10.143	10.130	11.702	11.779
	SD	0.361	0.401	0.491	0.552	0.668	0.677	0.424	0.478
		$p = 0.438$		$p = 0.617$		$p = 0.955$		$p = 0.694$	
Stature (cm)	Mean	118.8	117.1	127.3	128.0	139.1	140.2	150.0	146.8
	SD	5.9	5.9	9.0	6.6	8.5	7.2	9.0	4.5
		$p = 0.429$		$p = 0.792$		$p = 0.698$		$p = 0.308$	
Mass (kg)	Mean	23.53	22.21	28.94	29.35	38.88	35.84	46.76	45.70
	SD	4.40	3.44	7.31	5.45	9.00	8.92	13.00	11.38
		$p = 0.346$		$p = 0.844$		$p = 0.356$		$p = 0.841$	

5.1.2. Movement-ABC Scores

Descriptive statistics for the M-ABC total and sub-scores are presented in Table 5.2.

Using the Mann-Whitney U test, significant differences between the TD and DCD groups, at each age-band for total score and three sub-scores were found, except at age-band 3 for balls skills and at age-band 4 for manual dexterity and balls skills. Significant differences for these three group comparisons were not found due to the DCD groups higher sub-scores at the older age-bands. These findings are addressed in the discussion.

Table 5.2: Movement-ABC scores and sub-scores by groups.

		DCD	TD	DCD	TD	DCD	TD	DCD	TD
		<i>Age-band 1</i>	<i>Age-band 1</i>	<i>Age-band 2</i>	<i>Age-band 2</i>	<i>Age-band 3</i>	<i>Age-band 3</i>	<i>Age-band 4</i>	<i>Age-band 4</i>
	Gender	8m:9F	8m:8F	9m:8F	12m:9F	8m:9F	7m:7F	7m:4F	4m:7F
	N	17.0	16.0	17.0	21.0	17.0	14.0	11.0	11.0
M-ABC	Median	13.0	4.0	12.5	4.5	13.5	7.3	12.0	5.0
Total	Minimum	10.0	0.0	10.0	1.0	10.0	2.5	10.0	1.0
Score	Maximum	21.0	7.0	23.0	7.5	28.0	9.5	17.0	7.5
		$p < 0.001$		$p < 0.001$		$p < 0.001$		$p < 0.001$	
Manual	Median	7.0	2.8	5.0	1.0	8.5	4.0	2.0	0.5
Dexterity	Minimum	2.5	0.0	0.0	0.0	2.0	0.5	0.0	0.0
Score	Maximum	11.5	6.0	13.0	6.0	13.5	8.0	10.5	5.0
		$p < 0.001$		$p < 0.001$		$p = 0.002$		$p = 0.051^{\#}$	
Ball skills	Median	3.0	0.0	6.0	2.0	1.0	0.0	0.0	0.5
Score	Minimum	1.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
	Maximum	8.0	3.0	11.5	5.0	10.0	3.0	6.0	6.0
		$p < 0.001$		$p < 0.001$		$p = 0.070^{\#}$		$p = 0.525^{\#}$	
Balance	Median	2.0	0.0	2.0	0.5	4.0	2.0	7.0	3.0
Score	Minimum	0.0	0.0	0.0	0.0	2.0	0.0	3.0	0.0
	Maximum	6.0	2.0	9.0	5.5	8.0	5.5	10.0	6.0
		$p = 0.004$		$p = 0.005$		$p = 0.006$		$p = 0.001$	

[#] Indicates, no significant difference between DCD and TD group at that age-band

Based on the available literature it was decided not to include gender as an independent variable. Whilst gender differences have been found for some motor tasks (see Piek, Baynam & Barrett, 2006), those that specifically assessed vertical jump found no significant differences between genders below the age of 12 years (Butterfield et al., 2004; Malina et al., 2004; Thomas & French, 1985). Furthermore, previous DCD research involving motor tasks have also included mixed gender groups with male-to-female ratios of 19:5 (Gueze, 2003) and 22:10 (Johnston et al., 2002) respectively.

5.2. Equipment

All M-ABC equipment used for the specific age-band was provided in the test kit (Henderson & Sugden, 1992). A portable stadiometer (Mentone Education Centre, Design number 1013522), shown in Figure 5.1, was used to measure stretch stature. The tape measure has an elongated base which protrudes horizontally; this is placed on the vertex of the child's head. The base of the tape measure can slide up and down the vertical pole, measuring to the nearest 0.1 cm.



Figure 5.1: The portable stadiometer (Mentone Education Centre, Design number 1013522) used to measure stretch stature.

Kinetic and derived variables were measured using a strain gauge forceplate (VUplate; Australia). The forceplate attached to a 60 kg steel base (dimensions: 61 cm x 45 cm x 15cm) was taken from the research laboratory at ACU, Melbourne, Victoria and relocated to the classroom. A custom built housing (dimensions: 170 cm x 110 cm x 15 cm) was used to surround the forceplate providing a level surface beyond the dimensions of the forceplate. The additional area surrounding did not contact the forceplate, but provided a safe landing zone should a participant miss the plate upon landing. Data were collected at 700Hz, a higher sample rate used in the measurement of jumping (Bosco, 1992), although a need for higher frequencies above 1000 Hz has been recommended in some literature (Street, McMillan, Board, Rasmsmussen & Heneghan, 2001). The chosen sampling rate permitted three seconds of data collection. Three seconds ensured that the whole movement from the initial command to start through to landing and regaining a stationary upright stance was captured.

The forceplate was placed at the opposite end of the classroom to that used for the M-ABC data collection. Floor vibration was minimised by the use of high density rubber matting (15mm recycled rubber pavers: density: $850\text{kg}\cdot\text{m}^3$) placed beneath the forceplate. Total noise in the force signal was assessed during the forceplate calibration procedures (VUplate version 1.2) before each participant stood on the plate. Total noise (mean standard deviation) was estimated to be $\pm 1.5\text{ N}$ (CV = 0.6%) from the force signal during flight from 10 randomly selected jumps (Appendix 9).

All kinematic measures were in 2-D from a single-camera set-up (Panasonic Colour CCTV; 50Hz; model no. WV-CL830/G) with a Computar™ camera lens (model no. H6Z0812, 8-45 mm, 1:1.2), with the shutter set at 1/1000 s. The sagittal movement was recorded onto a VHS tape (NEC E-195), using a super video VHS Cassette Recorder (Panasonic; model no. AG4700). Previously, 60 Hz, the US NTSC video standard has been deemed sufficient to detect differences in timing of joint reversals and peak velocity differences between proximal and distal joints of each segment (Aragón-Vargas & Gross, 1997b). A camera height of 1.35 m (forceplate to centre of lens) was used due to the short stature and jump height of the participants. The location of the camera and forceplate is shown in Figure 5.2. The camera (front of lens) was located 10 m from the centre of the forceplate. This was the maximum distance that the camera could be located from the middle of the forceplate, due to the room dimensions, but, sufficient to minimise perspective and parallax error (Lythgo & Begg, 2004). The camera was positioned to capture the right hand side of the participants with its optical axis oriented perpendicular to the sagittal plane. The camera's field of view was 3.5m: width x 2.6m: height. The jumping movement was captured in the centre of the field of view to further minimise any perspective and parallax error (Lythgo & Begg, 2004).

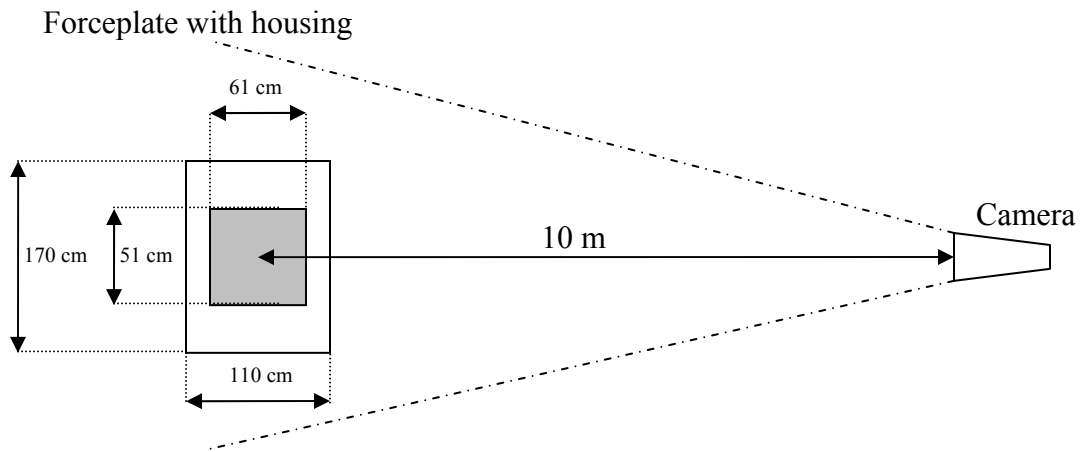


Figure 5.2: Camera, forceplate and housing position.

Calibration of the 2D measurement plane was conducted in accordance with the guidelines in the Peak Motus manual (Peak Technologies Inc, USA.), which are explained in detail in Appendix 8. Horizontal calibration was performed by filming reflective markers (dimension: 2 cm²) that were placed 1.50m apart on a steel rod before and after each testing session. The calibration rod provided a 2D scale reference for the subsequent video analysis of jumping performance.

The forceplate was enclosed by using three portable screens. The surrounding windows and walls were all covered in black sheets, providing a darkened room required for the kinematic data collection. A floodlight (ARLEC HL 18; 250 Watts) was placed directly behind the camera lens so as to provide illumination of the joint markers.

5.3. Procedures

5.3.1. Movement-ABC

All data were collected at the school during normal school operating hours over a period of three weeks. Being located at the school minimised disruption to normal school activities. A classroom used partly as a gymnasium at the school was made available for the entire duration of testing. Sufficient space was available to allow the individual components of the assessment (manual dexterity, ball skills and balance) to be tested at a series of stations. Screens were used to ensure privacy and also to minimise distraction. The classroom was well ventilated and large windows provided natural light with a polished board floor. The location of the school and classroom was free from noise and other distractions.

Assessments began at 0900hrs following morning assembly through to 1600hrs, the time of school closure. Children's activities the day before the assessment were not controlled. However, it is unlikely that children at this age would have participated in such vigorous activity the day before as to negatively affect the assessments. To avoid the affects of fatigue on the day of assessment no structured physical activity was performed by the participants before the assessment. In addition, the assessment was performed at a pace determined by the participant. Overall, the time to complete the assessment was between 20-30 minutes per participant, depending upon the child's ability.

Research assistants administered the M-ABC, in accordance with the guidelines outlined by Henderson & Sugden, (1992 p 36), for screening large numbers of children. Small groups of children ($n = 6$) from the same age-band were accompanied from the classroom to the testing venue and assessed individually. All research assistants was familiarised with the testing kit contents and knowledge of item instructions by mean of tutorials at the University. For consistency, each research assistant was assigned to conduct specific items depending on the age-band being assessed. Printed instructions for the specific items were available for each assistant to ensure correct completion of the tasks. Research assistants were briefed to monitor the participants during the assessment for signs of fatigue, loss in concentration and motivation. If the research assistant had reason to suspend the assessment, based on observations or upon request from the participant, a short break of approximately 10 minutes was permitted after which the participant returned to complete the assessment. Observation of a noticeable change in behaviour or mood of the participant was sufficient to suspend assessment. This, however, was not required at anytime throughout the assessments.

5.3.2. Physical Characteristics

5.3.2.1. Stretch Stature

Following the completion of the M-ABC, stretch stature was measured for every participant using a portable stadiometer (Mentone Education Centre, Design number 1013522; measurements 1mm), following the guidelines of Ross and Marfell-Jones, (1991 p. 235). Participants removed footwear and stood erect with heels together and arms hanging naturally. The researcher applied a stretch force by cupping the child's head and applying gentle traction alongside the mastoid processes. The measurement for stature was taken as the maximal distance from the floor to the vertex of the head. Stretch stature was used in order to control for diurnal changes in stature caused by compression of the spine (Ross & Marfell-Jones, 1991).

5.3.2.2 Bodyweight and Body Mass

Bodyweight (including shoes, clothing and markers) was measured on the forceplate during a period of quiet standing for 3 seconds. During the time of quiet standing a stable bodyweight was attained and saved on electronic file. Bodyweight was used to report the participant's body mass and calculated using the Equation 5.1 below:

$$\text{Bodymass}(kg) = \frac{\text{Bodyweight}(N)}{\text{gravity}(m \cdot s^{-2})} \quad \dots\dots\dots \text{Equation (5.1)}$$

Body weight was also used in the error analysis of the equipment (see Appendix 9).

5.3.3. Maximal Vertical Jump Protocol

The children wore dark tight fitting clothing and runners or other suitable shoes.

Adhesive passive reflective markers (3M reflective tape: 7610WS – high gain sheeting; dimensions: 2 cm square) were attached to known anatomical landmarks (reference points) by an accredited level one anthropometrist (International Society for the Advancement of Kinanthropometry). The markers were placed on the right side of the body at eight body landmarks. They were: centre of head (superior to the tragus of the ear or at the upper margin of the zygomatic bone at that point); shoulder (acromiale, superior and lateral border or the acromion process midway between the anterior and posterior borders of the deltoid when viewed from the side); elbow (proximal and lateral border of the head of the radius); wrist (ulnar styloid process); hip (greater trochanter); knee (lateral femoral condyle); ankle (lateral malleolus); and toe (5th metatarsal) (for more detail refer to Figure A1 in the Appendix 5 and Figure A2 in Appendix 6).

Once joint markers were securely placed and checked, the participant was given time to become accustomed to the markers. During the time allowed for familiarisation, the participant performed activities including jogging, hopping, jumping and skipping, which served as a warm-up for the jumping task. The duration of the ‘warm-up’ time varied but in all cases exceeded three minutes. When ready, the child stood still in the centre of the platform to allow bodyweight to be measured.

Three to five sub-maximal warm-up jumps were performed following the measurement of bodyweight. The sub-maximal jumps allowed familiarisation with the jumping protocol and ensured the participants were comfortable with landing back on the forceplate. Once the sub-maximal practice jumps were completed, a short break of less than two minutes was allowed. During this break the participant was given the following instructions by the researcher: “when I say ready, in your own time, jump as high as possible”. Following this instruction, the first of three maximal vertical jump attempts were completed. Before each jump, a card was used to code the video footage. The information contained on the card included the participant’s ID number and jump number. The command of ‘ready’ was used by the researcher to indicate to the participant when the automatic trigger for the forceplate was armed. Then, in their own time, the participant initiated the movement and attempted to jump as high as possible, before landing back on the forceplate safely and returning to an upright position. No attempt was made to control the jumping movement and no instructions were provided regarding the depth of crouch or how to use the upper body limbs. The limited instruction provided by the researcher was assumed to promote a jumping movement by the child that was self-selected and that reflected a ‘natural performance’. Following the first attempt, a rest period of 2-3 minutes was permitted before a second jump was attempted. Another 2-3 minute rest period followed before the final jump was performed. The time required to perform the three jumps took no longer than 20 minutes (including the familiarisation).

The best performance from three jumping attempts has been suggested by investigators to be sufficient (e.g., Harman et al., 1990). Some jump studies have used five attempts (e.g., Feltner et al., 1999) and one as many as 20 attempts (Falk et al., 1997). Three maximal jumps were considered satisfactory for this study. Further trials were considered to increase the risk of fatigue and loss of motivation. The concern of fatigue associated with DCD children during repeated movements has been previously discussed in the literature (e.g., Hands & Larkin, 2002).

All three maximal jump attempts were initiated from a standard posture. A stationary and upright position was used with a stance that was naturally adopted. Additional jumps were performed only when markers came off during jumping. This occurred twice during the data collection for one TD and one DCD child; one and two additional jumps were completed respectively, so that three jumps were recorded. No additional jumps were required for any other reason.

5.4. Data

5.4.1. Kinematic Parameters

5.4.1.1. Joint and Segmental Angles

For the purposes of this study bilateral symmetry was assumed (Winter, 1995) and the reference markers defined a six-segment model of the body: 1) trunk, 2) upper arm, 3) forearm and hand, 4) thigh, 5) shank and 6) foot (Jensen & Phillips, 1991). Relative joint angles were calculated for elbow, hip, knee, and ankle; and absolute angles were calculated for the, shoulder, trunk, thigh and shank segments (Figure 5.3)

The absolute shoulder angle consisted of the elbow marker (proximal), shoulder marker (axis) and the ground-based vertical axis (distal). The distal marker (vertical axis) was chosen to replace the hip joint to avoid the difficulties of marker occlusion experienced in the pilot work.

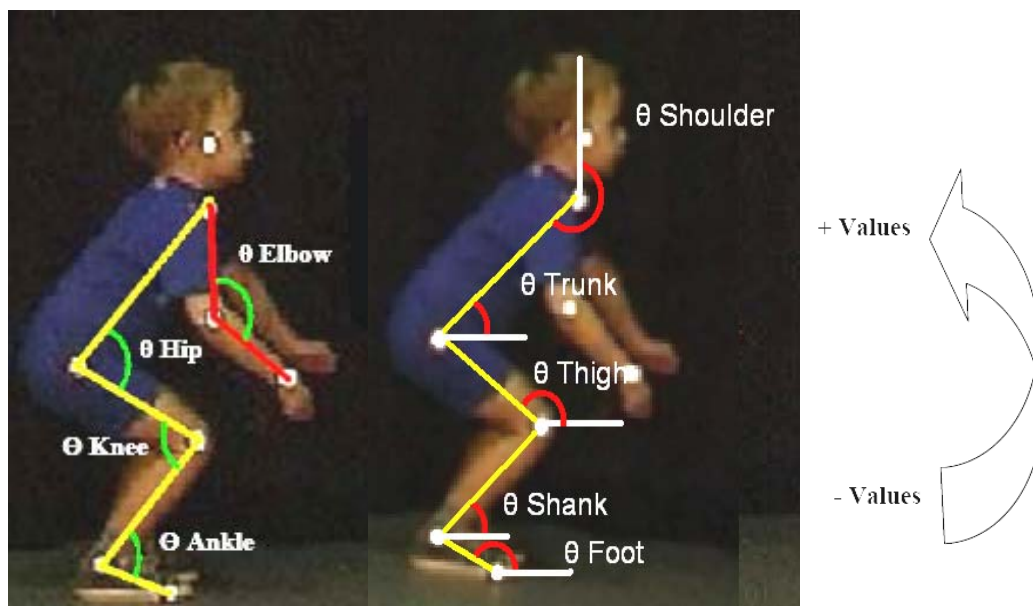


Figure 5.3: Absolute segmental angles and Relative joint angles (The arrow on the right identifies the direction of the positive motion, anticlockwise).

Once the highest jump was identified from the forceplate data, the Peak Motus Motion Measurement System (Version 8: Peak Performance Technologies Inc., USA) was used to determine the 2D spatial coordinate positions (Z, Y) of the joint markers (Appendix 5). The kinematic data were extracted by manual digitisation using the following standardised procedure. The video frames captured were divided into two separate fields by the Peak Motus software to give a 50 Hz sampling rate. For the purposes of data smoothing, digitising started eight fields before the initial movement (first visible movement) and finished eight fields after landing (first visible contact with the forceplate by the participant). Take-off was the reference point (event) used to synchronise the kinetic (forceplate) and kinematic (video) data. Take-off was determined visually using the Peak Motus software. The video was advanced until the feet were free from the force plate (Bobbert & van Ingen Schenau, 1988). The field that corresponded to ‘feet free’ from the force plate was then tagged as the “take-off” event in the software and used as a reference point.

Data processing included filtering using the Data Conditioner program in the Peak Motus software. The data were smoothed using the Butterworth 4th Order Zero Lag Filter. The cut-off frequency was determined using the optimal filtering option calculated by the Jackson Knee Method Data (Peak Motus Manual: Version 8.0). The conditioner interface permits visual confirmation of the cut-off frequency by displaying other frequency cut-off options. The visual inspection was completed for each parameter for each participant.

However, no changes from the optimal method were required. Following processing, all joint and segmental angles and angular velocities were calculated and exported.

Joint and segmental orientations at take-off were extracted. These included: θ Hip; θ Knee; θ Ankle; θ Elbow; θ Shoulder; θ Trunk; θ Thigh; θ Shank and θ Foot. The VCOM is dependent upon the combined velocities of all the individual joints (Bobbert & van Soest, 2001). Therefore, for each joint and segment, angular velocity at take-off was calculated. In addition, the peak angular velocity and when it occurred relative to the instant of take-off was recorded for each joint and segment. This was achieved by counting the number of samples (fields) between the instant of interest (e.g., peak angular velocity for the hip) and the instant of take-off. The number of samples was then multiplied by 0.02 s (50Hz).

The low point of SCOM was determined from the kinetic data and represented the end of the downward movement of the whole body. From this known instant of low point relative to take-off, the number of samples before take-off was calculated by dividing the duration from low point to take-off by 0.02s to convert into the nearest whole number of samples (Equation 5.2). From the data file, the number of frames was then manually counted from take-off to find the instant of low point and the joint and segmental orientations at that instant were recorded.

$$\text{Number of samples from Take-off (nearest whole number)} = \frac{t_{lp} - t_{TO}}{0.02} \quad \text{Equation (5.2)}$$

Where: t_{lp} was the instant of low point and t_{TO} was the instant of take-off

5.4.1.2. Duration of Knee Transition Phase

In previous literature the transition phase during the countermovement of a jump has been identified by knee joint angular data. This phase occurs when the knee angular velocity ranges between $+30 \text{ degrees}\cdot\text{s}^{-1}$ and $-30 \text{ degrees}\cdot\text{s}^{-1}$ in relation to deepest knee flexion (Rodacki, Fowler & Bennet, 2002). This period was derived from the number of samples within this angular velocity range ($\pm 30^\circ\cdot\text{s}^{-1}$) multiplied by the sample rate (0.02s). Poor control can be identified by an extended duration of the knee joint transition phase due to unwanted collapsing of the knee (Larkin & Hoare, 1991), hence this variable was of interest.

5.4.1.3. Joint Reversals

The neuromuscular coordination of the jumping movement was quantified using individual joint kinematic variables previously used by Jensen et al. (1994). Absolute joint reversals were calculated for the shoulder, hip, knee and ankle. Absolute timing of joint reversal occurred at the instant a joint changed from flexion to extension relative to take-off (Jensen et al., 1994). This was achieved by counting the number of frames from the joint reversal to the instant of take-off. The number of frames was then multiplied by 0.02 s (50Hz). Relative timing of joint and segmental reversals was also expressed as a

percentage of the duration of the jump cycle (i.e., the time between the instant of minimum VGRF and the instant of take-off).

5.4.1.4. Velocity Reversals

Peak velocity (extension) reversals were determined as the time from peak angular velocity for a joint to the instant of take-off. The joints used for this variable were hip, knee and ankle. The number of frames was counted from the instant of a peak angular reversal for the hip, knee or ankle and the instant of take-off, then multiplied by 0.02 to give the time, in seconds.

5.4.1.5. Segmental Coordination

Four variables used to describe the patterns of segmental coordination were also determined. These variables have previously been used in studies of adult vertical jumping (Hudson, 1986) and vertical jumping in children (Clark et al., 1989). These four variables, which describe the temporal relationship between inter-segmental angles (where the delay was measured with respect to the proximal joint), were:

- temporal delay between the initiation of hip [H] extension reversal and knee [K] extension reversal [H - K];
- temporal delay between the initiation of knee [K] extension reversal and the time of ankle[A] extension reversal [K - A];

- temporal delay between the instant of peak hip (H) angular extension velocity and the instant of peak knee (K) angular extension velocity [H – K]; and
- temporal delay between the instant of peak knee (K) angular extension velocity and the instant of peak ankle (A) angular extension velocity [K - A].

5.4.2. Kinetic Parameters

The kinetic (VGRF) data collection was started by an automatic trigger once the participant initiated a downward movement, and terminated after three seconds of sampling. The automatic trigger was set at -3 N from the BW reading and selected in preference to the manual trigger as previously used in earlier pilot work. By using the automatic trigger the time constraint placed on the participant during the initiation and execution of the jumping movement was removed. Removing the requirement to initiate and execute the whole jumping movement following a command to ‘jump’ was an important consideration for the present study, because of the age and associated planning difficulties reported throughout the DCD literature. Generally, children with DCD display a more varied and slower reaction and movement time, which adversely influences the execution of gross motor tasks such as jumping (Huh et al., 1998; Parker & Larkin, 2003; Raynor, 1998; Smyth & Glencross, 1986; Williams, 2002).

5.4.2.1. Jump Height

Essentially, a process of double integration was used to derive the centre of mass displacement (SCOM) from the acceleration data. The reader is referred to Appendix 11

(General Kinetic Analysis) for a detailed presentation of this method. The COM is the “point at which the mass is evenly distributed” (Hamill & Knutzen, 2003, p.385) and is commonly used to identify the acceleration, velocity and displacement of the whole body.

From the instantaneous SCOM during the jumping movement, jump height was derived as shown in Figure 5.4. Jump height was the difference between the SCOM from quiet standing height (reference taken from the measurement of bodyweight) and peak SCOM (Bobbert et al., 1996).

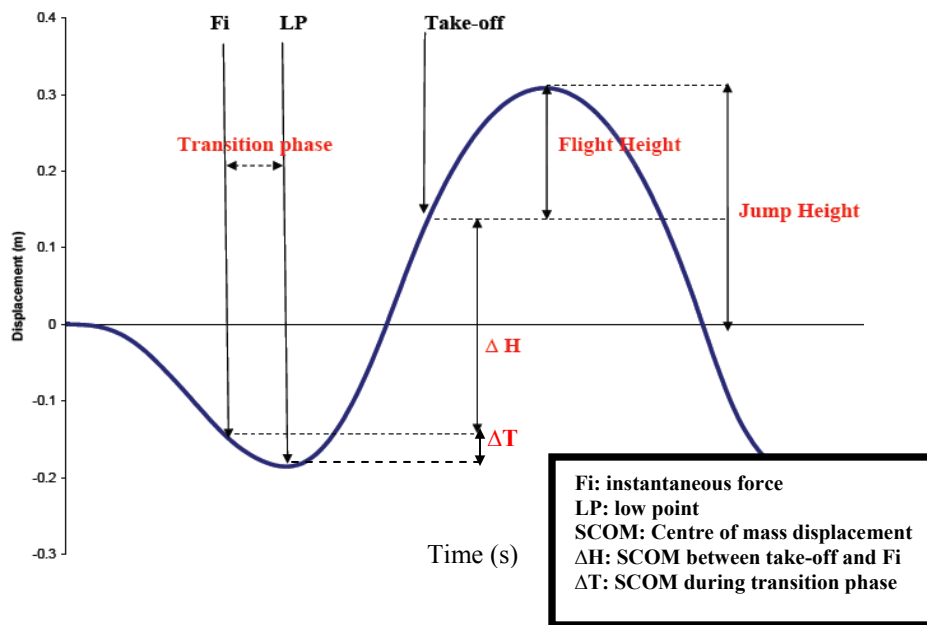


Figure 5.4: Key instants of the centre of mass displacement (SCOM) throughout the jump movement.

Jump height reported includes the sum of SCOM at take-off and flight height (SCOM during the flight phase) as shown in Figure 5.4. The SCOM at take-off was a particular interest for the present study because developmental literature indicates that qualitatively, children who display a poor movement pattern fail to fully extend the whole body at take-

off (Larkin & Hoare, 1991). The SCOM at take-off was therefore used to give an indication of the extent of the whole body extension.

For the forceplate data, the instant of take-off was defined as the instant the body departed from the forceplate. Take-off, was determined when the VGRF was equal to or within 3 N of negative BW. The threshold value (3 N) was established from the error analysis described in the appendices (refer to Appendix 9 and 10). Once established, the instant of take-off was also used as a point of reference for other timing variables (Bosco, Komi, Pulli, Pittera & Montonev, 1982). The difference between jump height and SCOM at take-off was referred to as flight height (Figure 5.4).

The duration of the whole jumping movement (jump cycle) was determined from the instant of minimum force (peak negative VGRF) to the instant of take-off (Jensen et al., 1994). From practical experience and the data generated from pilot work, the instant of minimum VGRF was the preferred starting point to define the jumping cycle. The previous use of a threshold value elsewhere in the literature (Feltner et al., 1999) of 4 N did not produce consistent timing and was too sensitive (typical error = ± 0.096 s: CV = 14.9 %). The duration before the instant of minimum VGRF appears to be too variable and stability of measures becomes more acceptable when minimum VGRF is used as the starting point of the jumping movement. Jump cycle time was therefore calculated as the time difference between the instant of minimum VGRF and take-off (Figure 5.5). For all timing variables, jump cycle was used for the calculation of percentage, where 0% was equal to the instant of minimum VGRF and take-off occurred at 100% of jump cycle.

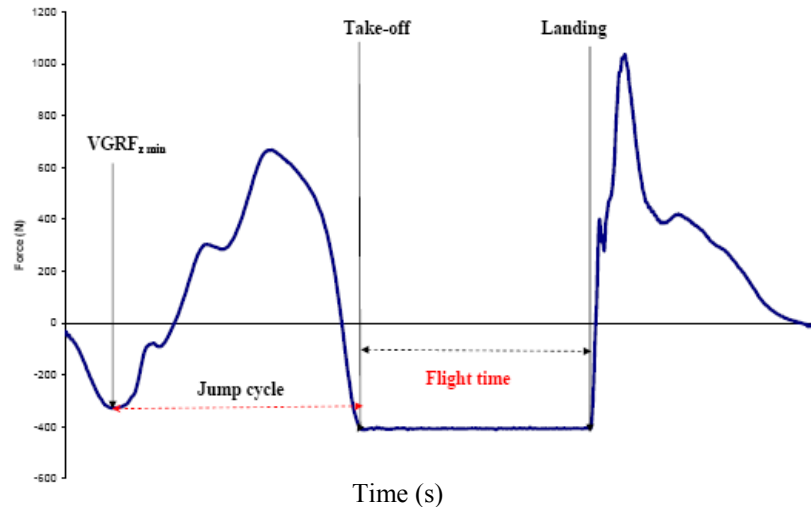


Figure 5.5: Jump cycle from the instant of minimum vertical ground reaction force ($VGRF_{min}$) to the instant of take-off, and flight time from take-off to landing.

All SCOM variables (e.g., jump height) were normalised as previously described by dividing the variable by the participant's stature (Aragón-Vargas & Gross, 1997a; Butterfield et al., 2004), in order to account for its influence on jumping performance in children (Bosco & Gutstafson, 1983).

5.4.2.2. Vertical Velocity of the Centre of Mass

Vertical Velocity of the Centre of Mass (VCOM) at take-off is important to jumping and represents the coordinated effort of all joints and segments to propel the body upwards. Using the instantaneous VCOM, $VCOM_{take-off}$ was found from the already determined instant of take-off (Figure 5.6). In addition, the instances and magnitudes of minimum and peak VCOM were identified and recorded (Figure 5.6).

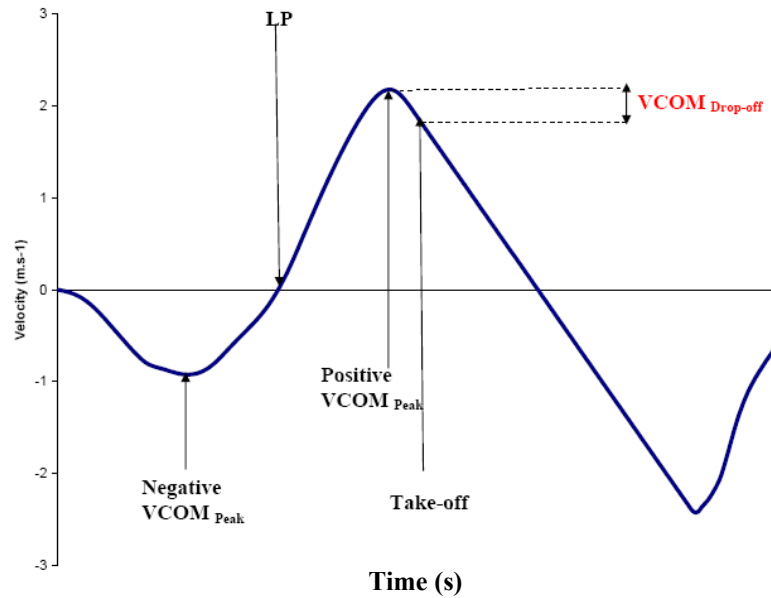


Figure 5.6: Vertical velocity of the centre of mass (VCOM) used to determine VCOM at take-off, magnitudes of VCOM (peak) for positive and negative directions and VCOM drop-off

The peak VCOM determined from the instantaneous VCOM data was used as a measure of movement velocity. To maximise jump height, reaching peak VCOM as close to the instant of take-off requires an efficient and effective coordination of the body's segments (Bobbert & van Soest, 2001). The time elapsed between peak VCOM and take-off has previously been used to reflect the quality of neuromuscular coordination of jumping in children aged between five to eight year olds (Falk et al., 1997).

5.4.2.3. Force and Power Variables

Jumping is an explosive movement, requiring the body to actively develop force. From the force data, timing and magnitudes of Ground Reaction Forces (GRF) in the vertical

(V) and horizontal (H) directions (Minimum VGRF; Peak VGRF; Minimum HGRF; Peak HGRF) throughout the jumping movement were collected (Figures 5.7 and 5.8).

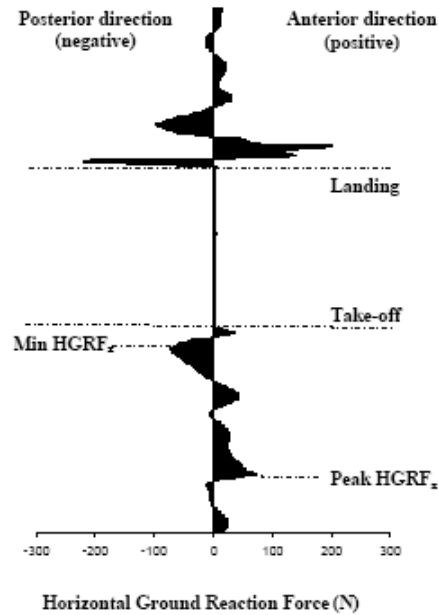


Figure 5.7: Horizontal ground reaction force (HGRF) during a single maximal vertical jump attempt. Anterior and posterior directions are reflected by peak and minimal (min) HGRF respectively.

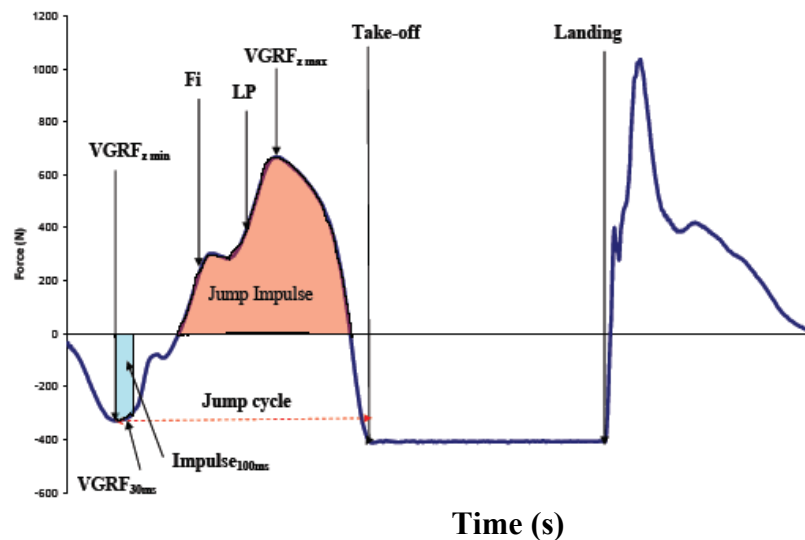


Figure 5.8: Vertical ground reaction force (VGRF) curve throughout the jumping movement.

The nature of the jumping task requires the body to be displaced in the vertical direction maximally, therefore, horizontal displacement should be minimised. The minimum HGRF represents the maximal force in the posterior direction whilst the peak positive HGRF represents the peak anterior force (Figure 5.7). In addition, the magnitude of horizontal displacement of the toe marker, from take-off to landing was used to quantify the departure from the initial position.

Using the impulse-momentum relationship, the explosive movement of jumping is determined by the force produced over a period of time. Vertical Jump Impulse (Jump impulse), which is determined by force applied above body weight during the concentric phase was calculated using the Equation A10 described by Dowling & Vamos, (1993) (Appendix 11), and identified as the red shaded area in Figure 5.8. All force variables were reported with normalising by bodyweight due to the inherent relationship between force and mass (Bosco & Gustafson, 1983).

Power, the product of force and velocity, is an important quantity. Due to the force – velocity trade-off, the lack of ability to produce force at high velocities may distinguish children identified with DCD from those who are TD (Raynor, 2001). From the instantaneous power curve (refer to Appendix 11 Equation A7), peak positive power (Equation A8) and average positive power (Equation A11) were calculated. The power variables are presented graphically in Figure 5.9.

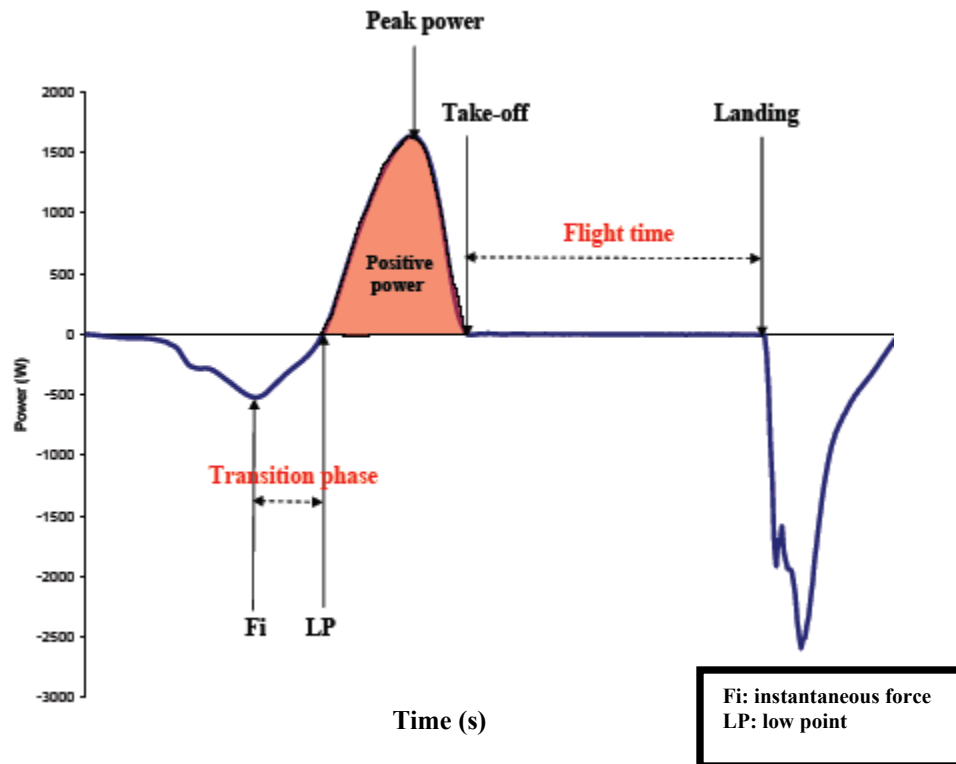


Figure 5.9: The power curve throughout the jumping movement. Average power is shown as the red shaded area.

The magnitude and instant of peak positive power was recorded. In addition, the average positive power was calculated by calculating the area under the positive power curve (left shaded area in Figure 5.9) divided by the number of samples (Bosco et al., 1982; Bosco, 1992; Harman et al., 1991). The instant following peak negative power was noted, and represented the instant of Instantaneous Force (Fi) (Bosco, 1992). Peak positive power and average power were both reported relative to body mass ($\text{W} \cdot \text{kg}^{-1}$) in accordance with the recommendations for samples of children (Bar-Or, 1996; Docherty, 1996; Falk et al., 1997).

5.4.2.4. Countermovement

From instantaneous SCOM, the low point of the countermovement was identified as the lowest value (Figure 5.4). This was considered to represent the amplitude of the countermovement from quiet stance. With the instant of low point established, the force at this moment was recorded. In addition, the time interval from the low point to take-off was used to define the duration of the concentric phase, where the body moved upwards until take-off.

5.4.2.5. Eccentric Variables

The lack of strength to control the downward phase has been suggested as a reason for poor performance by children. The initial eccentric loading is the ability to develop force rapidly following peak negative VGRF and was quantified as the force produced at 30 ms (starting strength) and impulse over the first 100 ms (refer to Equation A15 in Appendix 11). Both measures give an indication of the force developed and experienced during the initial moments of the eccentric loading phase (Wilson, Lyttle, Ostrowski & Murphy, 1995). In addition, the Peak negative VCOM (min VCOM) was used to indicate the peak velocity of the countermovement (Kibele, 1998).

5.4.2.6. Transition Variables

At higher velocities in the transitions from isokinetic knee extension to flexion, children identified with DCD have been reported as having particular difficulties and exhibiting co-activation (Raynor, 2001). For jumping, the transition occurs between the eccentric and concentric phases of the countermovement. The coordinated effort of the lower limbs predominantly involves the hip, knee and ankle joints, therefore the task demands in this investigation were assumed to be greater and more complex than the isokinetic tasks used by Raynor. The increased complexity imposed in the jump task should therefore improve the chance of identifying any differences between DCD and TD groups.

Instantaneous force (F_i) was determined at the point when the mechanical power first moves in a positive (upward) direction (Bosco, 1992). In Figure 5.9, this instant is the first sample following the instant of peak negative power as shown in Figure 5.9.

It has been proposed that once muscles are activated they act quasi-isometrically, holding the muscle fascial at its optimal length, whilst the tendon is stretched, permitting energy to be stored (e.g., Kubo et al., 1999). F_i was used to represent this instant. The duration between the instant of F_i and low point gives the time of the transition from the eccentric to concentric actions, which was referred to as the transition phase (F_i time – low point time) (Bosco, 1992). In the literature, this has also been referred to as the stretching time (Kiebele, 1998).

The SCOM that occurs during the transition phase (ΔT) may provide useful information about the properties of the muscle-tendon-complex (MTC). The ΔT was calculated, which has also been referred to as the stretching distance elsewhere in the literature (Kiebele, 1998). The ΔT was calculated as the difference between the SCOM at the instant of F_i and SCOM at low point (Figure 5.4 and Equation A11).

The smooth transition from flexion to joint extension requires precise inter-muscular coordination. Leg stiffness (K_{leg}) was calculated by using the Equation 5.3 (Bosco, 1992) and used as an indirect measure of lower leg muscle co-activation during the transition from flexion to extension.

$$K_{leg} \text{ (leg stiffness) } \text{KN}\cdot\text{m}^{-1} = \frac{(F_i + BW)}{\Delta H} \quad \text{.....Equation (5.3)}$$

Where: $\Delta H = \text{SCOM}_{TO} \text{ (instant of take-off)} - \text{SCOM}_{Fi} \text{ (instant of eccentric-concentric transition)}$ (Bosco, 1992)

Previously K_{leg} has been calculated using the hip marker to represent the SCOM (Wang et al., 2003). However it is clear that errors due to the lower sampling frequency of video (50 Hz) would be large. In addition, the hip marker displacement does not represent the changes in position of the relatively large mass of the trunk. Therefore, using SCOM derived kinetically from the VGRF during the jumping movement was more appropriate in this study. Leg stiffness has also been calculated for running and hopping using the VGRF at low point (Farley & Gonzalez, 1996). This method by Farley and Gonzalez (1996) assumed that maximal VGRF coincides with the instant of low point for the

calculation of K_{leg} . However, when arm-swing is used in a countermovement jump it can impose an additional transfer to the VGRF curve (Payne et al., 1968). The difference in timing was illustrated from earlier pilot work, where low point occurred at 0.457 ± 0.092 s and the instant of mean peak VGRF followed at 0.587 ± 0.114 s into the jumping movement (Williams et al., 2004). Therefore, using the peak VGRF is not warranted for jumps that involve arm-swing. The calculation of K_{leg} used in this study (Bosco, 1992) was developed specifically for jump assessments using forceplate data.

5.5. Statistical Analysis

The software package SPSS Version 14 for Windows (SPSS Inc, Chicago, Illinois), was used for all statistics.

5.5.1. Normal Distribution Testing

All kinetic and kinematic variables were tested for normal distribution. The criteria were set following a process of critical appraisal as described by Peat and Barton (2005). The data were considered not normally distributed if breaches occurred in any of the following criteria:

1. the Shapiro-Wilk test > 0.05 ;
2. the difference between mean and the median was less than 10%;
3. the mean was less than the standard deviation doubled;

4. skewness score was within ± 1.00 ;
5. kurtosis score was within ± 1.00 ;
6. skewness score divided by the standard error score was within ± 1.96 ; and
7. kurtosis score divided by the standard error score was within ± 1.96

Data that were non-normally distributed were log- transformed using the natural logarithm (LN) and re-evaluated for normal distribution. If this failed alternative transformations were made depending on the type of distribution found (Tabachnick & Fidell, 2001). When log transformed data were used in the statistical analysis, they have been identified in the corresponding table of descriptive statistics in the results section. To avoid confusion for the reader, log-transformed data have not been presented, rather, the original units of measurement have been reported.

5.5.2. Hypothesis Testing

The major null hypothesis for this investigation was:

Null hypothesis 1: There would be no difference between TD and DCD groups for jump height.

This null hypothesis was tested by means of a univariate ANOVA.

Null hypothesis 2: No difference between TD and DCD groups will be found for SCOM during the jump movement.

Three key instants during the jumping movement were identified (low point, take-off and flight height). The SCOM at these instants were grouped and the second null hypothesis tested MANOVA.

The SCOM derived from the kinetic data describes a hypothetical position of the whole body at the defined instant in time, such as take-off. From kinematic analysis, further understanding of the movement can be obtained, by knowing how the joints and segments are organised at that point. It is possible that SCOM may be equal at a given instant, but the joints and segmental angles may be different. Therefore, joint and segmental angles at low point and take-off were analysed. Four MANOVAS were used to test for differences in: 1) joint angles at low point; 2) segmental angles at low point; 3) joint angles at take-off; and 4) segmental angles at take-off.

Null Hypothesis 3a: No difference in the velocity variables will be found between TD and DCD groups.

Once the feet have departed from the ground, it is VCOM at take-off that determines jump performance (Hatze, 1998), therefore, to explain the anticipated group differences in flight height further, the third null hypothesis above was tested.

The dependent variables used in this MANOVA to describe VCOM were: VCOM at take-off; time elapsed between peak VCOM and take-off; and peak VCOM. Three additional analyses were performed to explain VCOM at take-off at the sub-level. MANOVA was used to identify differences between groups for: 1) joint angular velocities at take-off; 2) segmental angular velocities at take-off; and 3) delay in adjacent velocities reversals and peak joint velocities reversals.

Null Hypothesis 3b: No difference in force and power variables will be found between TD and DCD groups.

Vertical jumping is a recognised assessment for explosive lower limb strength. As DCD children were expected to exhibit lower force and power outputs, measures of these variables attained from this movement were expected to differentiate between groups and age-bands. Therefore the above null hypothesis was tested.

The force variables (jump impulse; min VGRF; peak VGRF; min HGRF; and peak HGRF) and power variables (peak power; timing of peak power; and average power) were analysed separately. MANOVA was used to test for differences between DCD and TD children in each of these sets of variables.

Null Hypothesis 4: No difference in the countermovement at the eccentric, transition and concentric phases, will be found between TD and DCD groups.

The fourth level of the conceptual framework focused on a more detailed analysis of the countermovement already described at level 1 by the SCOM at low point and the corresponding sub-level (joint and segmental angles at low point). Differences in performance of the countermovement between groups were expected to explain differences in the variables identified in level 2 (VCOM, force and power). The countermovement performance formed the basis for the fourth null hypothesis:

For the purposes of analysis, the countermovement was divided into three phases, which consisted of the eccentric, transition and concentric phases. MANOVA was used to analyse the eccentric phase, which contained the following grouped variables: VGRF 30ms after min VGRF; impulse at 100ms; VGRF at low point; and duration of eccentric phase. The transition phase variables (F_i ; K_{leg} ; SCOM during the transition phase, duration of transition phase; and duration of knee transition) were grouped together and analysed by MANOVA. The concentric phase, which terminates at take-off contained five separate MANOVAs, which included grouped variables for: 1) joints range of motion; 2) segments range of motion; 3) absolute joint reversals; 4) relative joint reversals; and 5) delay between adjacent joint reversals.

Null Hypothesis 5: Group differences for jump measures will not increase at older age-bands.

Finally, as DCD children may choose to withdraw from physical activity at a young age, leading to further inhibition of their motor performance later in life, differences between TD and DCD groups were anticipated to be greatest at the older age-bands. Based on this expectation, the above final null hypothesis for this investigation was tested.

MANOVA has been extensively used in previous studies that investigated jumping in children (e.g., Clark et al., 1989; Jensen et al, 1994). Therefore, to compare previous work the same model of analysis was used in the current study. Potential violation of the underlying assumptions of the model throughout the previous work is high and generally disregarded on the basis that the analysis is robust. In the present study, it was anticipated that due to the nature of DCD (i.e., the wide range and level of coordination difficulties and the possibility that some DCD children will perform at TD levels in parts of the assessment), the group data would be highly variable. Furthermore, the number of tests performed and limited cell sizes can increase the probability of making either a type I or type II error; when the null hypothesis is accepted or rejected in error (Peat & Barton, 2005). Therefore, Pillai's Trace criterion instead of the more common Wilks' Lambda was used to evaluate multivariate significance (Tabachnick & Fidell, 2001). Pillai's Trace has previously been shown to be the most conservative criterion, robust to the violations of the MANOVA assumptions, such as sample size (Olson, 1979). The significance for

all MANOVA was accepted at below 0.05 (typically accepted in exercise science; Hopkins, 2000).

Multivariate outliers were identified with Mahalanobis distance ($p < 0.001$) using chi-square value with degrees of freedom equal to number of dependent variables (Tabachnick & Fidell, 2001). In extreme cases, outliers were removed when significant differences were identified (Tabachnick & Fidell, 2001). Box's M test was used for testing the assumption of multivariate homogeneity of variance-covariance matrices. A significance level of $p < 0.001$ was used for this test. Whilst at the univariate level, Levene's test was used ($p < 0.05$) to assess the homogeneity of variance.

When a significant multivariate effect was found ($p < 0.05$), an examination of the univariate/between-subjects effects were performed), these indicate which of the dependent variables contribute to the significant multivariate effect. To decrease the chance of making a type I error, a Bonferroni adjustment (i.e., $\alpha/\text{number of tests}$) was applied to the alpha level (Vincent, 2005). To report significant differences from the univariate analysis, less than the adjusted alpha, rather than the exact alpha was reported (i.e., when five dependent variables were assessed and one returned $p = 0.002$ in the univariate analysis, it was reported as $p < 0.010$; less than the adjusted alpha, not the exact alpha).

Furthermore, when significant multivariate main effects across age-bands were found a polynomial linear contrast was used to test for a significant trend across age-bands in

addition to the univariate analysis (Reported as, trend $p = 0.002$, for example). When a significant group by age interaction was found ($p < 0.05$), comparisons across age-bands for a group or between TD and DCD groups at a specified age-band were conducted. A one-way ANOVA was used to evaluate differences across age-bands (age-band 1, 2, 3, and 4) and when a main effect was found a trend test (e.g., weighted polynomial linear) was used to assess the significance of the increase or decrease across age-bands (Peat & Barton, 2005). To evaluate differences between groups (TD and DCD) at a specific age-band (either age-band 1, 2, 3 or 4) independent t-tests were used.

CHAPTER VI

RESULTS

The results are presented in accordance with the conceptual framework for the enquiry outlined in Chapter 4. Descriptive statistics are reported in tables for each DCD and TD age-band (1 - 4) and combined age-bands (total). The tables are organised to reflect how the dependent variables were organised for each MANOVA analysis. Following the descriptive statistics table, a MANOVA summary for the main effects is presented (when used). In the case of a significant main effect, only the significant univariate post-hoc analyses have been reported.

6.1. Jump Height

The null hypothesis of no difference between TD and DCD groups for jump height was tested by means of a 2 x 4 ANOVA. The descriptive statistics for jump height are listed in Table 6.1.

Table 6.1: Mean and standard deviations (SD) for jump height (JH).

<i>Group</i>	<i>Age-band</i>	<i>JH †‡ (cm)</i>	
		<i>Mean</i>	<i>SD</i>
DCD	1	27.2	6.3
	2	26	3.1
	3	30.1	6
	4	29.7	4.6
Total		28.1	5.4
TD	1	28.6	6.4
	2	29.1	6.1
	3	32.8	7.1
	4	36.3	10.3
Total		31.1	7.7

[†] Indicates a significant univariate main effect between groups

[‡] Indicates a significant univariate main effect between age-bands

Overall the TD group jumped 3.0 cm (11%) higher ($F(1,116) = 8.760, p = 0.004, \eta^2 = 0.070$) than the DCD group (TD group = 31.1 ± 7.7 cm; DCD group = 28.1 ± 5.4 cm), the null hypothesis was, therefore, rejected. However, the small effect size was noted and confirmed by the overlap of the standard deviation bars between groups at each age-band in jump height (Figure 6.1). Across age-bands, a significant difference ($F(3,116) = 5.093, p = 0.002, \eta^2 = 0.116$, trend $p = 0.001$) between age-band 1 and age-band 4 was 5.1 cm for jump height. No group by age-band effect was found.

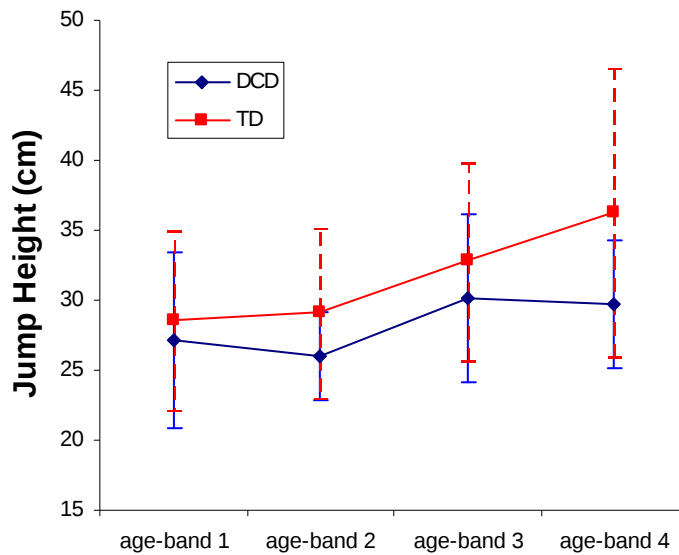


Figure 6.1: Mean jump height (cm) between TD and DCD groups.

6.2. Displacement of the Body's Centre of Mass Variables

The second null hypothesis that there will be no difference between TD and DCD for the SCOM variables during the jumping movement was examined by means of a 2 x 4

MANOVA. The descriptive statistics for the grouped SCOM variables are listed in Table 6.2. These variables were: SCOM at low point, SCOM at take-off and flight height.

Table 6.2: Mean and standard deviations (SD) for displacement of centre of mass position (SCOM) at low point (LP), flight height (FH) and at take-off (TO).

<i>Group</i>	<i>Age-band</i>	<i>SCOM position at LP[†] (cm)</i>		<i>FH^{†‡} (cm)</i>		<i>SCOM at TO (cm)</i>	
		<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>
DCD	1	-8.4	4.8	11.3	4.9	15.9	4.8
	2	-10.9	3.0	13.8	2.3	12.2	2.1
	3	-13.4	3.8	16.3	4.2	13.8	3.3
	4	-13.9	4.4	16.4	4.2	13.2	2.4
Total		-11.4	4.5	14.3	4.5	13.8	3.6
TD	1	-9.3	4.7	14.0	2.7	14.6	5.1
	2	-12.4	3.7	15.3	4.1	13.8	4.6
	3	-13.2	3.7	19.0	3.6	13.8	4.6
	4	-17.1	5.1	20.3	4.2	16.0	6.8
Total		-12.6	4.9	16.7	4.4	14.4	5.1

[†] Indicates a significant univariate main effect between groups

[‡] Indicates a significant univariate main effect between age-bands

From the MANOVA summary of the SCOM variables (Table 6.3), significant multivariate main effects for group and age-band were found, but no significant group by age-band interaction was observed.

Table 6.3: MANOVA summary of centre of mass displacement variables.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta²
Group [†]	0.119	3	114	5.130	0.002	0.119
Age-band [‡]	0.424	9	348	6.364	<0.001	0.141
Group by age-band	0.067	9	348	0.885	0.539	0.022

[†] Indicates a significant univariate main effect between groups

[‡] Indicates a significant univariate main effect between age-bands

From the univariate analysis, Flight height was 2.4 cm (17%) greater ($F(1,116) = 14.390$, $p < 0.0167$, $\eta^2 = 0.110$) in the TD group (16.7 ± 4.2 cm) compared to the DCD (14.3 ± 4.5 cm) group. The group differences are shown in Figure 6.2. No significant group differences were found for the SCOM either at take-off or low point.

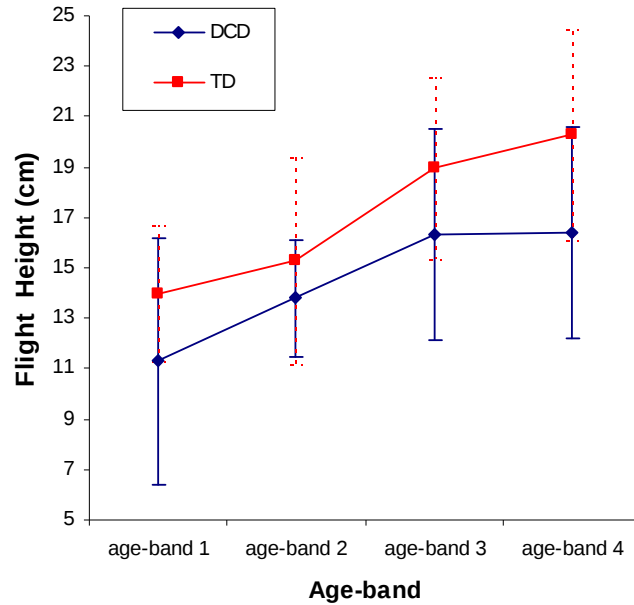


Figure 6.2: Mean flight height (cm) between TD and DCD groups.

In the analysis by age-band, flight height, ($F(3,116) = 14.084$, $p < 0.0167$, $\eta^2 = 0.267$, trend $p < 0.001$) and SCOM at low point ($F(3,116) = 13.018$, $p < 0.0167$, $\eta^2 = 0.252$, trend $p < 0.001$) were both significantly different. The mean difference between age-band 1 and age-band 4 was 2.9 cm for flight height and 6.7cm for SCOM at low point. No significant differences for SCOM at take-off were found across age-bands.

6.2.1. Joint and Segmental Angles at Take-off and at the Low Point

The null hypotheses of no difference between TD and DCD groups for the joint and segmental variables at both low point and take-off were examined by means of four separate 2 x 4 MANOVAs. The first MANOVA examined the joint angles at take-off, which included the shoulder, elbow, hip, knee and ankle. The descriptive statistics for these variables are presented in Table 6.4.

Table 6.4: Mean and standard deviations (SD) for joint angles at take-off (TO).

<i>Group</i>	<i>Age-band</i>	<i>Shoulder at TO (°)</i>		<i>Elbow at TO (°)</i>		<i>Hip at TO (°)</i>		<i>Knee at TO (°)</i>		<i>Ankle at TO (°)</i>	
		<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>	<i>Mean</i>	<i>SD</i>
DCD	1	133.2	85.5	143.1	60.5	173.2	14.5	173.9	12.9	140.7	12.7
	2	140.9	101.5	104.5	104.3	176.8	11.7	180.2	8.2	141.2	7.6
	3	112.7	103.2	126.8	104.3	175.7	9.8	178.6	11.2	138.8	16.6
	4	110.2	91.0	138.3	44.6	180.5	7.7	180.2	6.9	144.1	9.1
	Total	125.6	94.6	127.2	85.0	176.2	11.5	178.0	10.5	140.9	12.1
TD	1	169.7	89.7	95.2	99.7	168.8	7.6	175.4	8.3	142.2	9.4
	2	103.9	92.3	125.5	83.4	173.9	9.3	175.0	7.1	142.3	10.2
	3	76.0	76.1	156.4	55.5	174.6	8.3	174.9	4.9	139.0	6.0
	4	134.3	86.0	100.7	82.2	175.9	9.3	177.1	8.3	138.2	10.9
	Total	120.0	91.9	120.3	83.9	173.1	8.8	175.5	7.1	140.8	9.3

No significant main effects were found for the joint angles at take-off (Table 6.5).

Overall, at take-off, the sample's mean shoulder angle was $122.8 \pm 92.9^\circ$, elbow joint was $123.7 \pm 84.2^\circ$, hip angle was $174.6 \pm 10.3^\circ$, knee angle was $176.7 \pm 9.0^\circ$ and ankle angle was $140.8 \pm 10.7^\circ$.

Table 6.5: MANOVA summary of joint angles at take-off.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.053	5	112	1.247	0.292	0.053
Age-band	0.158	15	342	1.270	0.219	0.053
Group by age-band	0.114	15	342	0.900	0.565	0.038

The descriptive statistics for trunk, thigh, shank, foot segmental angles at take-off are listed in Table 6.6.

Table 6.6: Mean and standard deviations (SD) for segmental angles at take-off (TO).

Group	Age-band	<i>Trunk at TO</i> (°)		<i>Thigh at TO</i> (°)		<i>Shank at TO</i> (°)		<i>Foot at TO</i> (°)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	82.4	6.9	89.1	9.0	84.4	12.4	122.4	9.4
	2	81.3	7.8	84.4	5.9	84.5	4.8	123.3	6.2
	3	81.5	5.8	85.5	6.8	84.0	9.5	119.4	7.9
	4	84.1	6.6	83.5	4.1	83.7	4.4	119.8	6.5
	Total	82.1	6.7	85.8	7.0	84.2	8.5	121.3	7.7
TD	1	78.7	5.6	89.9	4.6	85.3	5.5	122.9	7.5
	2	82.4	10.2	87.2	4.3	81.9	4.6	118.3	11.0
	3	81.3	5.7	86.5	3.4	81.3	3.1	122.3	5.2
	4	81.3	5.2	85.6	5.4	82.6	6.3	124.5	7.4
	Total	81.0	7.4	87.5	4.6	82.8	5.0	121.5	8.6

As found for the joint angles, no significant multivariate main effects were observed for the segmental variables at take-off (Table 6.7). Overall, at take-off the sample mean trunk angle was $81.6 \pm 7.1^\circ$, thigh angle was $86.6 \pm 6.0^\circ$, shank angle was $83.5 \pm 7.0^\circ$ and foot angle was $121.4 \pm 8.1^\circ$.

Table 6.7: MANOVA summary of segmental angles at take-off.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.031	4	113	0.913	0.459	0.031
Age-band	0.130	12	345	1.303	0.215	0.043
Group by age-band	0.087	12	345	0.859	0.589	0.029

To explain the SCOM at the low point, the joint and segmental angles were analysed.

Descriptive statistics for the grouped dependent variables, elbow, shoulder, hip, knee and ankle joints angles at low point are presented in Table 6.8.

Table 6.8: Mean and standard deviations (SD) for joint angles at the instant of low point.

Group	Age-band	Shoulder at low point (°)		Elbow at low point (°)		Hip at low point (°)		Knee at low point (°)		Ankle at low point (°)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	135.5	36.3	203.4	19.1	111.3	28.1	110.9	20.8	87.6	7.4
	2	122.1	43.9	193.7	17.8	112.2	14.4	115.5	14.7	86.4	7.5
	3	135.0	26.4	208.7	22.9	107.2	17.1	110.9	15.3	87.3	10.0
	4	115.7	26.9	202.3	19.4	111.3	17.6	113.3	13.9	85.1	7.8
Total		128.2	34.9	202.0	20.3	110.4	19.8	112.6	16.3	86.7	8.1
TD	1	133.9	44.2	195.1	23.6	107.5	21.8	109.9	18.5	89.4	8.2
	2	136.6	34.3	196.5	22.0	106.9	19.5	106.9	12.8	87.4	8.5
	3	125.7	31.7	211.0	32.0	108.6	18.2	116.0	10.5	89.9	4.4
	4	122.3	34.6	213.4	25.6	101.3	25.6	105.8	12.3	80.9	12.6
Total		130.9	36.2	202.4	26.2	106.4	20.6	109.5	14.2	87.3	9.0

No significant multivariate main effects were found for the joint angles at low point

(Table 6.9). Overall, at the instant of low point, the sample's mean shoulder angle was

202.2 ± 23.3°, elbow joint was 129.5 ± 35.4°, hip angle was 108.4 ± 20.2°, knee angle

was 111.0 ± 15.3°; and ankle angle was 87.0 ± 8.5°.

Table 6.9: MANOVA summary of joint angles at low point.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.020	5	112	0.458	0.807	0.020
Age-band	0.175	15	342	1.412	0.139	0.058
Group by age-band	0.120	15	342	0.946	0.513	0.040

Descriptive statistics for the trunk, thigh, shank, foot segmental angles at low point are presented in Table 6.10.

Table 6.10: Mean and standard deviations (SD) for segmental angles at the instant of low point (LP).

Group	Age-band	Trunk at LP (°)		Thigh at LP (°)		Shank at LP (°)		Foot at LP (°)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	59.0	13.4	119.1	28.7	58.7	7.2	151.0	6.8
	2	55.1	9.9	122.8	8.8	58.3	7.5	151.9	3.5
	3	53.4	10.0	126.2	10.2	57.1	7.5	149.8	6.6
	4	53.6	12.6	122.2	8.0	55.5	7.0	141.5	30.9
	Total	55.4	11.4	122.6	16.8	57.6	7.2	149.2	14.0
TD	1	57.4	10.9	125.3	22.9	59.5	8.4	150.0	3.6
	2	55.2	12.2	128.3	9.7	55.1	5.7	145.0	14.4
	3	52.0	14.1	119.4	17.2	58.1	6.1	148.2	5.2
	4	48.2	18.4	119.8	24.7	52.7	6.4	151.8	8.5
	Total	53.8	13.6	124.0	18.4	56.5	7.0	148.2	9.8

No significant multivariate main effects were found for the segmental variables at take-off (Table 6.11). Overall, at the instant of low point, the sample's mean trunk angle was $54.6 \pm 12.6^\circ$, thigh angle was $123.3 \pm 17.5^\circ$, shank angle was $57.0 \pm 7.1^\circ$ and the foot angle at take-off was $148.7 \pm 12.1^\circ$ for the sample.

Table 6.11: MANOVA summary of segmental angles at low point.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.014	4	113	0.389	0.816	0.014
Age-band	0.144	12	345	1.451	0.141	0.048
Group by age-band	0.115	12	345	1.147	0.321	0.038

In summary, the second null hypothesis was rejected, on the basis of differences between TD and DCD groups in the SCOM variables following take-off. However, the positioning of the COM, joints and segments, whilst in contact with the ground was no different between groups. When analysed by age-band, only flight height and the SCOM at low point were both found to be different. The difference in SCOM at low point could not be explained, however, by group differences in joint and segmental angles at that instant. No differences across age-bands were also found for the SCOM position at take-off, and joint and segmental angle variables at all instants throughout the movement.

6.3. Velocity, Force and Power Variables

6.3.1. Vertical Velocity of the Centre of Mass Variables

To test the third (3a) hypothesis, VCOM variables (VCOM at take-off, peak VCOM and the time elapsed between the instant of peak VCOM and take-off) were grouped together and a MANOVA performed. During the data screening, however, an extreme outlier for the time duration between peak VCOM and take-off in the DCD group age-band 3 was found (Figure 6.3). The effect of this outlier can be seen in Figure 6.4 (left panel). This outlier was removed since it is truly aberrant and not representative of any observations

in the sample (Hair, Anderson, Tatham & Black, 2000; Peat & Barton, 2005). The right side panel of Figure 6.4 shows the data with the outlier removed. The reduction in the size of the standard deviation bar as a result of the outlier being removed suggests that it was justified. However, additional outliers were identified (Figure 6.3) and all were DCD children. It was decided not to remove these from the analysis. They were deemed truly representative of the nature of the DCD population and retained in the analysis and their inclusion did not affect the outcome of the analysis.

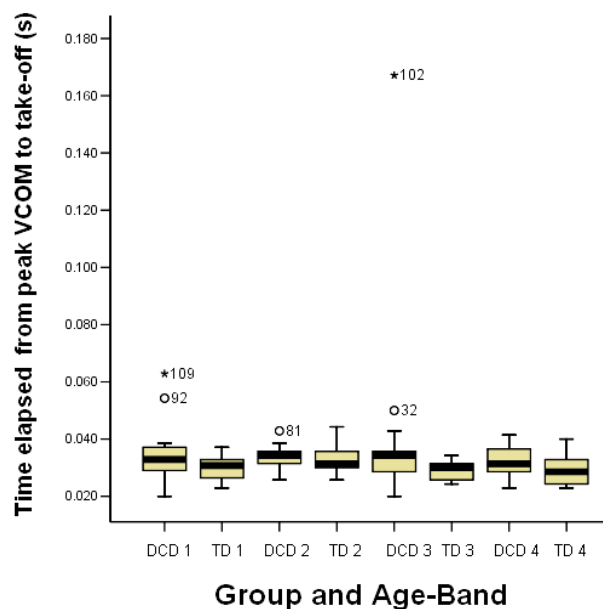


Figure 6.3: Box plots to show the distribution of scores and the extreme outlier (102) for the time elapsed from peak vertical velocity of the centre of mass (peak VCOM) to take-off (s).

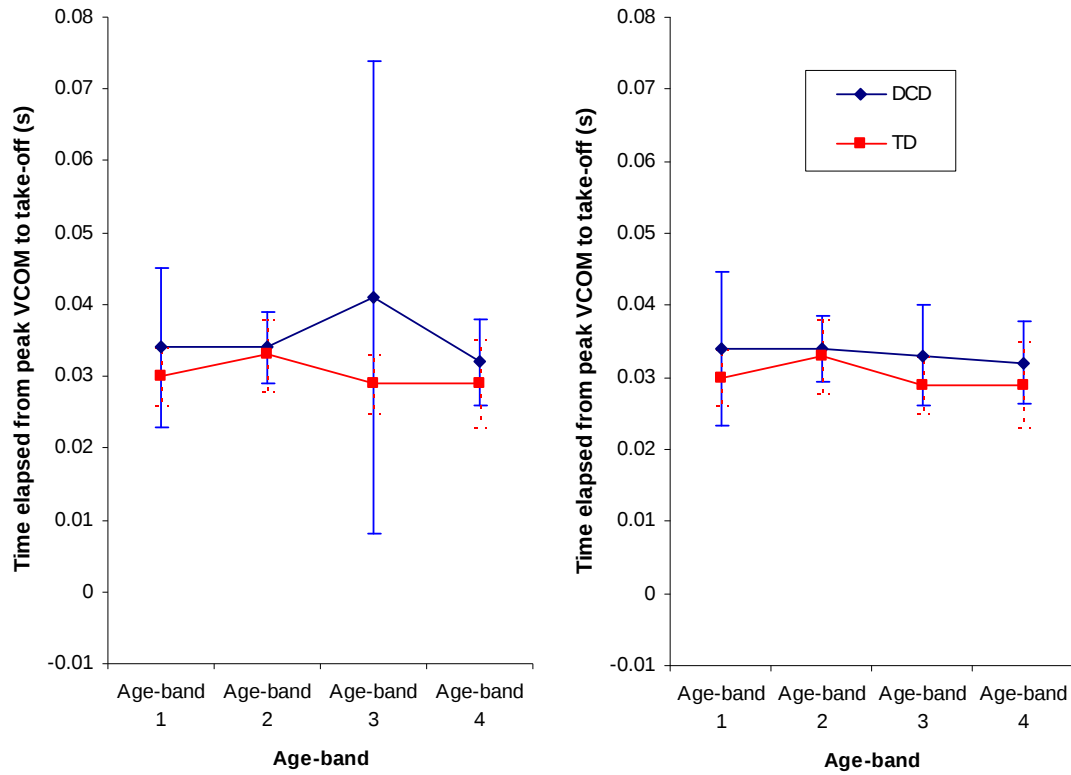


Figure 6.4: Time elapsed from peak vertical velocity of the centre of mass (peak VCOM) to take-off (s). Complete data set (left panel) and data following the outlier removed (right panel).

The descriptive statistics for the VCOM variables used in the MANOVA are listed in Table 6.12.

Table 6.12: Mean and standard deviations (SD) for peak vertical velocity of the centre of mass (peak VCOM), VCOM at take-off ($\text{m}\cdot\text{s}^{-1}$) and the duration from the instant of peak velocity to take-off (Time elapsed).

Group	Age-band	VCOM at TO ^{†‡} ($\text{m}\cdot\text{s}^{-1}$)		Time elapsed ^{†‡} (s)		peak VCOM ^{†‡} ($\text{m}\cdot\text{s}^{-1}$)	
		Mean	SD	Mean	SD	Mean	SD
DCD	1	1.43	0.28	0.034	0.011	1.70	0.22
	2	1.63	0.14	0.034	0.005	1.84	0.12
	3	1.76	0.20	0.033**	0.007	1.95	0.17
	4	1.79	0.25	0.032	0.006	1.99	0.23
	Total	1.64	0.26	0.033	0.007	1.86	0.21
TD	1	1.62	0.15	0.030	0.004	1.81	0.14
	2	1.66	0.18	0.033	0.005	1.90	0.16
	3	1.92	0.18	0.029	0.004	2.10	0.17
	4	2.00	0.21	0.029	0.006	2.18	0.19
	Total	1.77	0.23	0.030	0.005	1.97	0.21

**** Outlier removed from analysis (0.041 ± 0.033 s)**

[†] Indicates a significant univariate main effect between groups

[‡] Indicates a significant univariate main effect between age-bands

From the MANOVA performed on the VCOM variables, a significant multivariate main effect for group and age-band were found. No significant group by age-band interaction was found (Table 6.13).

Table 6.13 MANOVA of summary of velocity of the centre of mass variables.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.136	3	113	5.916	0.001	0.136
Age-band	0.445	9	345	6.680	<0.001	0.148
Group by age-band	0.055	9	345	0.712	0.698	0.018

From the univariate analysis, the TD group ($1.77 \pm 0.23 \text{ m}\cdot\text{s}^{-1}$) had a greater ($F(1,115) = 17.112$, $p < 0.0167$, $\text{eta}^2 = 0.130$) VCOM at take-off compared to the DCD group ($1.64 \pm 0.26 \text{ m}\cdot\text{s}^{-1}$). The differences in VCOM at take-off between groups are shown in Figure 6.5.

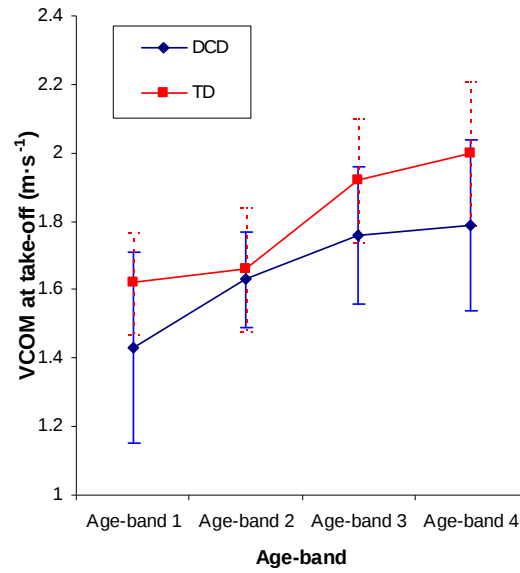


Figure 6.5: Mean vertical velocity of the centre of mass (VCOM) (m·s⁻¹) at take-off between TD and DCD groups.

Peak VCOM was also greater ($F(1,115) = 15.411, p < 0.0167, \eta^2 = 0.118$) for the TD group ($1.97 \pm 0.21 \text{ m·s}^{-1}$) compared to the DCD group ($1.86 \pm 0.21 \text{ m·s}^{-1}$). The instant of peak VCOM was also significantly closer ($F(1,115) = 7.833, p < 0.0125, \eta^2 = 0.064$) to take-off for the TD group ($0.030 \pm 0.005 \text{ s}$) than the DCD group ($0.033 \pm 0.007 \text{ s}$).

The differences in time elapsed from peak VCOM to take-off, between groups were shown previously in Figure 6.4. In addition, from the univariate analysis, significant differences were found across age-bands for VCOM at take-off ($F(3,115) = 20.736, p < 0.0167, \eta^2 = 0.351, \text{trend } p < 0.001$) and Peak VCOM ($F(3,115) = 21.401, p < 0.0167, \eta^2 = 0.358, \text{trend } p < 0.001$), but not the time elapsed from peak VCOM to take-off.

6.3.1.1. Joint and Segmental Angular Velocities at Take-off

At the sub-level, VCOM at take-off can be explained by the individual contributions of joint and segmental angular velocities at take-off. The descriptive statistics for shoulder, elbow, hip, knee and ankle joint angular velocities at take-off are listed in Table 6.14. These variables together represented the joint angular velocities at take-off and were tested using MANOVA.

Table 6.14: Mean and standard deviations (SD) for joint angular velocities at take-off (TO).

Group	Age-band	Shoulder angular velocity at TO ($^{\circ}\text{s}^{-1}$)		Elbow angular velocity at TO ($^{\circ}\text{s}^{-1}$)		Hip angular velocity at TO ($^{\circ}\text{s}^{-1}$)		Knee angular velocity at TO ($^{\circ}\text{s}^{-1}$)		Ankle velocity at TO ($^{\circ}\text{s}^{-1}$)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	-144.8	722.1	326.3	770.9	64.5	174.7	128.2	78.1	191.4	108.7
	2	-281.6	590.1	250.7	559.7	130.4	126.3	157.0	103.9	212.8	77.9
	3	-254.9	438.0	151.4	430.3	157.4	119.7	127.9	76.2	226.1	59.9
	4	-165.4	294.2	202.4	324.2	172.7	120.1	150.6	70.2	200.1	86.4
	Total	-216.2	544.2	235.6	555.3	127.2	141.5	140.0	83.4	208.3	83.9
TD	1	97.3	502.4	-143.3	606.3	71.5	152.3	109.3	82.7	226.5	80.3
	2	-333.3	572.2	255.3	429.9	173.9	146.9	192.7	96.2	227.8	85.9
	3	-255.7	642.7	269.6	511.7	208.3	83.2	195.9	113.9	228.4	66.5
	4	101.4	408.9	-126.0	426.1	143.3	132.1	156.7	123.5	199.8	85.3
	Total	-127.5	570.9	88.0	525.4	149.8	140.4	165.5	106.2	222.6	79.1

From the MANOVA performed, no significant multivariate main effects were found for the joint angular velocities at take-off (Table 6.15).

Table 6.15: MANOVA summary of joint angular velocities at take-off.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.069	5	112	1.668	0.148	0.069
Age-band	0.174	15	342	1.407	0.141	0.058
Group by age-band	0.102	15	342	0.807	0.677	0.034

The descriptive statistics for the trunk, thigh, shank and foot segmental angular velocities at take-off are listed in Table 6.16. These grouped variables represented the segmental angular velocities at take-off.

Table 6.16: Mean and standard deviations (SD) for segmental angular velocities at take-off (TO).

Group	Age-band	<i>Trunk angular velocity at TO</i> (°·s ⁻¹)		<i>Thigh angular velocity at TO</i> (°·s ⁻¹)		<i>Shank angular velocity at TO</i> [†] (°·s ⁻¹)		<i>Foot angular velocity at TO</i> (°·s ⁻¹)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	32.2	76.2	-43.2	103.4	-14.8	102.8	-182.6	101.5
	2	58.6	56.5	-72.1	89.6	-0.9	86.5	-212.0	88.4
	3	80.5	64.4	-74.2	69.7	-3.1	105.7	-222.0	86.7
	4	84.2	69.7	-94.0	60.6	-16.5	120.2	-224.2	103.4
	Total	61.9	68.4	-68.6	84.2	-8.1	100.4	-208.8	93.6
TD	1	35.5	63.7	-36.5	100.1	21.3	67.0	-219.1	83.6
	2	59.5	59.9	-116.9	98.2	45.0	67.9	-188.8	92.1
	3	87.2	41.3	-123.0	75.6	63.4	65.5	-164.2	56.1
	4	109.9	139.3	-85.6	82.9	25.4	122.7	-184.4	76.0
	Total	68.5	80.1	-92.0	96.0	39.6	79.1	-190.3	80.6

[†] Indicates a significant univariate main effect between groups

From the MANOVA performed, a significant multivariate main effect between groups was only found for the segmental angular velocities only (Table 6.17).

Table 6.17: MANOVA summary of segmental angular velocities at take-off.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group [†]	0.084	4	113	2.599	0.040	0.084
Age-band	0.164	12	345	1.658	0.075	0.055
Group by age-band	0.107	12	345	1.068	0.386	0.036

From the univariate analysis, it was the shank angular velocity at take-off, which produced the explanation for the difference between groups ($F(1,116) = 7.971$, $p < 0.0125$, $\eta^2 = 0.064$). Shank angular velocity at take-off was greater for the TD group ($39.6 \pm 79.1^\circ\text{s}^{-1}$) than the DCD group ($-8.1 \pm 100.4^\circ\text{s}^{-1}$). The differences between the groups can be seen in Figure 6.6, where all mean values for the DCD groups are less than those in the TD group.

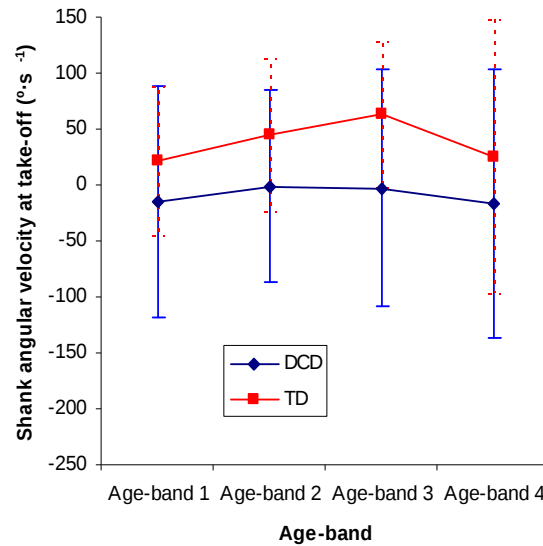


Figure 6.6: Mean shank angular velocity ($^\circ\text{s}^{-1}$) at take-off between TD and DCD groups.

6.3.1.2. Joint Velocity Reversals

The final sub-level analysis of VCOM variables examined the delay in hip, knee and ankle absolute reversals, and the delay between adjacent joints (H-K and K-A). The descriptive statistics for these variables are listed in Table 6.18. To meet the assumption of normal distribution for the MANOVA analysis, both the delays in adjacent joint reversals (H-K and K-A) were log transformed.

Table 6.18: Mean and standard deviations (SD) for absolute time of hip, knee and ankle velocity reversals (Ab Vel Rev) in relation to take-off, delay between hip-knee and knee-ankle peak velocity reversals.

Group	Age-band	Hip Ab Vel (s)		Knee Ab Vel (s)		Ankle Ab Vel (s)		Delay hip-knee peak velocity reversals (s)*		Delay knee- ankle peak velocity reversals (s)*	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	-0.11	0.05	-0.08	0.01	-0.07	0.02	0.03	0.05	0.02	0.02
	2	-0.08	0.02	-0.07	0.02	-0.06	0.02	0.01	0.02	0.01	0.02
	3	-0.09	0.03	-0.08	0.02	-0.06	0.01	0.01	0.02	0.02	0.02
	4	-0.09	0.02	-0.08	0.02	-0.07	0.01	0.00	0.02	0.02	0.02
	Total	-0.09	0.03	-0.08	0.02	-0.06	0.02	0.01	0.03	0.02	0.02
TD	1	-0.09	0.02	-0.08	0.01	-0.06	0.02	0.01	0.02	0.02	0.02
	2	-0.08	0.02	-0.07	0.01	-0.06	0.02	0.01	0.02	0.01	0.02
	3	-0.08	0.02	-0.07	0.02	-0.06	0.01	0.00	0.02	0.02	0.02
	4	-0.09	0.03	-0.09	0.02	-0.07	0.01	0.01	0.02	0.02	0.02
	Total	-0.08	0.02	-0.08	0.02	-0.06	0.02	0.01	0.02	0.02	0.02

* indicates that the variable was log transformed for the analysis

From the MANOVA, no significant multivariate main effect for group, age-band or interaction was found (Table 6.19). Overall, the sample's peak angular velocity occurred at the hip 0.01 ± 0.03 s before the knee, and 0.02 ± 0.02 s at the knee before the ankle.

This finding of a predominantly proximal to distal sequencing in the sample, but not the entire sample, is the same as that found for the adjacent joint velocity reversals and examined further in the discussion.

Table 6.19: MANOVA summary of joint angular velocities reversals.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.034	5	112	0.783	0.564	0.034
Age-band	0.158	15	342	1.266	0.221	0.053
Group by age-band	0.087	15	342	0.680	0.805	0.029

In summary, the third (3a) null hypothesis was rejected with differences between TD and DCD group found for peak VCOM and take-off VCOM. From the sub-level analysis, the shank angular velocity at take-off differentiated between the TD and DCD groups, the explanation for the group differences found in the time elapsed from peak VCOM to take-off, and also the magnitude of peak VCOM at take-off. No other differences were found for the joint and segmental velocities. Age-band effects were also observed for peak VCOM and take-off VCOM, with higher VCOM values at the older age-bands. No differences were found in the joint velocity reversals. The sequencing pattern was, therefore, no different between groups and across age-bands. Most individuals displayed the expected proximal to distal sequencing. However, the standard deviations for the variables allow for the possibility that some of the individuals from the sample did not display this expected sequencing of velocity reversals.

A key finding between DCD and TD groups was that the time of peak VCOM occurred significantly earlier before take-off in the DCD group, compared to the TD group. In addition, five outliers (one extreme) identified in the time elapsed from peak VCOM to take-off; all came from the DCD group from different age-bands. Unlike the other VCOM variables, the time elapsed from peak VCOM to take-off was not different across age-bands.

6.3.2. Force Output

To test the second part of the third hypothesis (3b) that was concerned with differences in force and power variables between TD and DCD groups. The force and power variables were grouped separately and analysed using two separate MANOVAs. The descriptive statistics for the grouped force variables (normalised peak HGRF, min HGRF, peak VGRF, min VGRF and jump impulse) are listed in Table 6.20. These variables represented the force output during the concentric phase.

Table 6.20: Mean and standard deviations (SD) for normalised minimum vertical ground reaction force (min VGRF), normalised Peak VGRF (peakVGRF), normalised minimum horizontal ground reaction force (minHGRF), normalised peak HGRF (peak HGRF) and normalised jump impulse.

Group	Age-band	<i>minVGRF</i> [‡]		<i>peakVGRF</i>		<i>minHGRF</i>		<i>peak HGRF</i>		<i>Jump impulse</i> ^{†‡}	
		(BW)		(BW)		(BW)		(BW)		(BW·s ⁻¹)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	-0.41	0.14	1.22	0.30	-0.17	0.05	0.15	0.07	0.217	0.036
	2	-0.60	0.16	1.56	0.36	-0.18	0.06	0.15	0.06	0.250	0.024
	3	-0.52	0.21	1.33	0.35	-0.16	0.07	0.13	0.05	0.266	0.026
	4	-0.60	0.20	1.48	0.54	-0.15	0.06	0.12	0.06	0.287	0.031
	Total	-0.53	0.19	1.39	0.40	-0.17	0.06	0.14	0.06	0.252	0.038
TD	1	-0.44	0.16	1.38	0.34	-0.20	0.06	0.13	0.04	0.237	0.027
	2	-0.50	0.13	1.27	0.25	-0.17	0.04	0.12	0.04	0.256	0.020
	3	-0.55	0.20	1.58	0.31	-0.18	0.05	0.11	0.04	0.281	0.024
	4	-0.54	0.20	1.37	0.37	-0.20	0.04	0.1	0.04	0.298	0.025
	Total	-0.50	0.17	1.38	0.33	-0.19	0.05	0.12	0.04	0.265	0.032

[†] Indicates a significant univariate main effect between groups

[‡] Indicates a significant univariate main effect between age-bands

From the MANOVA, a significant main effect for both group and age-band were found, but no significant interaction (Table 6.21).

Table 6.21: MANOVA summary of force variables.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group [†]	0.181	5	112	4.948	<0.001	0.181
Age-band [‡]	0.608	15	342	5.799	<0.001	0.203
Group by age-band	0.144	15	342	1.51	0.310	0.048

From the univariate analysis, normalised jump impulse for the TD group (0.265 ± 0.032 BW·s⁻¹) was significantly greater ($F(1,116) = 7.105$, $p < 0.010$, $\eta^2 = 0.058$) compared to the DCD group ($0.252 \pm .038$ BW·s⁻¹). Figure 6.7 shows these differences between the groups at each of the age-bands. No differences between the TD and DCD groups were

found for the normalised HGRF or VGRF magnitudes (min or peak). However, from the age-band analysis, normalised jump impulse was significantly different ($F(3,116) = 29.952, p < 0.010, \eta^2 = 0.437$, trend $p < 0.001$) by $0.065 \text{ BW}\cdot\text{s}^{-1}$ (29%) from age-band 1 ($0.228 \pm 0.033 \text{ BW}\cdot\text{s}^{-1}$) to age-band 4 ($0.293 \pm 0.029 \text{ BW}\cdot\text{s}^{-1}$). In addition, a significant difference ($F(3,116) = 4.331, p < 0.010, \eta^2 = 0.101$, trend $p = 0.006$) across age-bands was found for minimum VGRF, where the difference between age-band 1 ($-0.42 \pm 0.15 \text{ BW}$) and age-band 4 ($-0.57 \pm 0.20 \text{ BW}$) was -15 BW (35%).

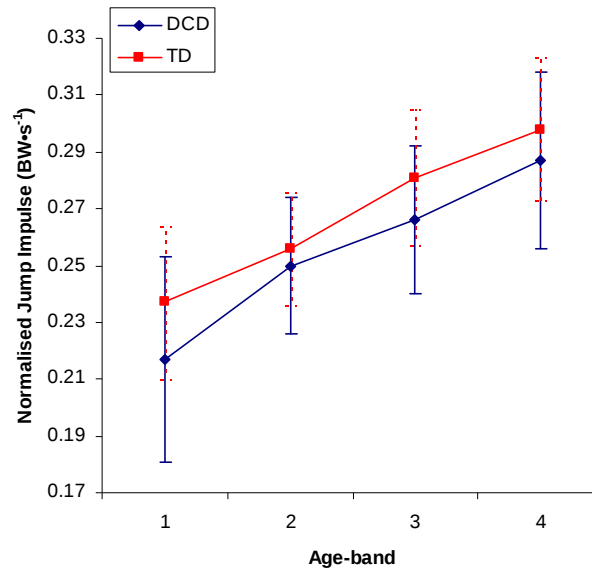


Figure 6.7: Normalised jump impulse ($\text{BW}\cdot\text{s}^{-1}$) between TD and DCD groups.

6.3.3. Power Output

The power variables: normalised peak power; average power; and time elapsed from the instant of peak power to take-off were tested by MANOVA. The descriptive statistics for these variables are listed in Table 6.22. These variables represented the timing and

magnitude of power output produced during the concentric phase. The data for time elapsed from the instant of peak power to take-off were log transformed to meet the assumption of normal distribution for the MANOVA analysis.

Table 6.22: Mean and standard deviations (SD) for normalised peak power output, normalised average power output and time elapsed from the instant of peak power to take-off.

Group	Age-band	Normalised Peak power output ^{†‡} (W·kg ⁻¹)		Normalised average power output [†] (W·kg ⁻¹)		Time elapsed from the instant of peak power to take-off (s) [*]	
		Mean	SD	Mean	SD	Mean	SD
DCD	1	28.3	4.7	14.4	4.2	0.071	0.014
	2	32.9	3.6	18.1	2.9	0.073	0.005
	3	33.7	5.0	18.4	3.5	0.071	0.008
	4	35.4	6.8	19.9	4.3	0.072	0.007
	Total	32.3	5.5	17.5	4.1	0.072	0.009
TD	1	30.5	3.6	17.4	2.1	0.068	0.005
	2	32.2	4.1	17.5	2.4	0.102	0.135
	3	39.3	4.7	20.2	2.5	0.069	0.006
	4	38.7	3.9	20.6	2.4	0.068	0.007
	Total	34.5	5.5	18.7	2.7	0.080	0.079

* Indicates that the variable was log transformed for the analysis

† Indicates a significant univariate main effect between groups

‡ Indicates a significant univariate main effect between age-bands

From the MANOVA, significant multivariate main effects for group and age-band were found. Additionally, a significant age by group interaction was achieved (Table 6.23).

Table 6.23: MANOVA summary of power output variables.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.082	3	114	3.394	0.020	0.082
Age-band	0.365	9	348	5.359	<0.001	0.122
Group by age-band	0.190	9	348	2.609	0.006	0.063

From the univariate analysis, normalised peak power was significantly greater ($F(1,116) = 9.910, p < 0.0167, \eta^2 = 0.058$) for the TD group ($34.5 \pm 5.5 \text{ W}\cdot\text{kg}^{-1}$) compared to the DCD group ($32.3 \pm 5.5 \text{ W}\cdot\text{kg}^{-1}$). The differences for normalised peak power between TD and DCD groups are illustrated in Figure 6.8. No other significant differences between TD and DCD groups for the power variables were found. Across age-bands normalised peak power ($F(3,116) = 18.485, p < 0.0167, \eta^2 = 0.323, \text{trend } p < 0.001$) and normalised average power ($F(3,116) = 10.785, p < 0.0167, \eta^2 = 0.218, \text{trend } p < 0.001$) were both significantly different. Normalised peak power was $29.4 \pm 4.3 \text{ W}\cdot\text{kg}^{-1}$ at age-band 1 compared to $37.1 \pm 5.7 \text{ W}\cdot\text{kg}^{-1}$ at age-band 4, whilst normalised average power was also larger at age-band 4 ($20.2 \pm 3.4 \text{ W}\cdot\text{kg}^{-1}$) compared to age-band 1 ($15.9 \pm 3.6 \text{ W}\cdot\text{kg}^{-1}$). No significant difference across age-bands was found for the time elapsed from the instant of peak power to take-off. A significant multivariate interaction was found for the power variables, however, when clarification was sought through a univariate analysis, no significant interactions were displayed for the three output dependent variables. When normalised peak power was compared at age-band 3, which displayed the largest difference between TD and DCD groups (DCD = $33.7 \pm 5.0 \text{ W}\cdot\text{kg}^{-1}$; TD = $39.3 \pm 4.7 \text{ W}\cdot\text{kg}^{-1}$), a significant difference ($t(29) = -3.158, p = 0.004, \text{ES} = 1.15$) was found. At the younger age-bands 1 and 2, however, normalised peak power for both groups was essentially the same (Figure 6.8).

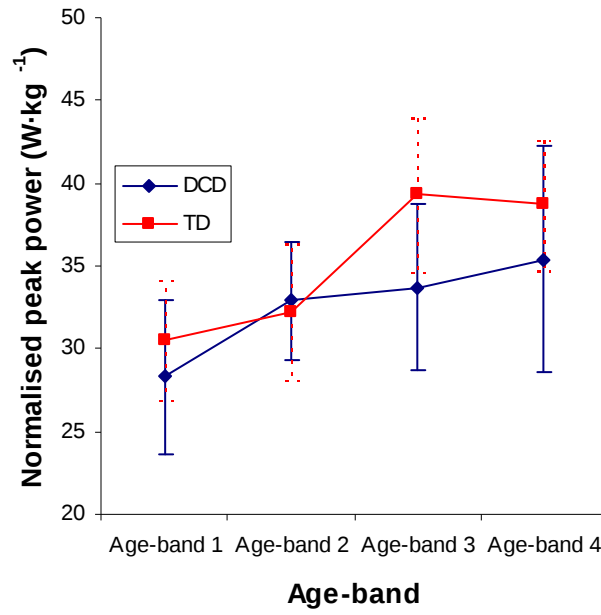


Figure 6.8: Normalised peak power ($\text{W}\cdot\text{kg}^{-1}$) between TD and DCD groups.

In summary, support for the rejection of the null hypothesis (3b) came from the finding that jump impulse was different between groups and across age-bands with age-band 4 values greater than age-band 1. However, other force variables were significantly different. For the power variables, differences between TD and DCD groups were found for normalised peak power as a result of the countermovement. Across the age-bands, both peak power and average power showed an increase at the older age-bands. Whilst no univariate interactions were found for each dependent variable, a significant difference was found at age-band 3 for peak power output.

6.4. Countermovement Variables

The fourth null hypothesis was that no difference would be found between groups for the countermovement. For analysis purposes, the countermovement was divided into three phases.

6.4.1. Eccentric phase

The first phase of the countermovement was the eccentric phase. The descriptive statistics for normalised VGRF 30ms after min VGRF, impulse at 100ms, VGRF at low point and duration of the eccentric phase are presented in Table 6.24. To meet the assumption of normal distribution, the data for the duration of the eccentric phase were log transformed.

Table 6.24: Mean and standard deviations (SD) for Normalised force at 30 ms post-minimum vertical ground reaction force (min VGRF), Normalised impulse at 100ms post-minimum, Normalised VGRF, force at low point (LP) and duration of the eccentric phase.

Group	Age-band	<i>Normalised VGRF 30ms after minVGRF (BW)</i>		<i>Normalised impulse at100ms (BW·s⁻¹)</i>		<i>Normalised VGRF at LP (BW)</i>		<i>Eccentric phase duration (s*)</i>	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	0.107	0.074	0.029	0.018	0.707	0.476	0.273	0.149
	2	0.134	0.064	0.032	0.017	1.201	0.491	0.204	0.054
	3	0.100	0.066	0.024	0.013	0.969	0.400	0.257	0.153
	4	0.128	0.083	0.038	0.033	1.207	0.570	0.218	0.068
	Total	0.116	0.071	0.030	0.020	1.003	0.511	0.240	0.119
TD	1	0.124	0.104	0.031	0.024	1.010	0.366	0.189	0.066
	2	0.113	0.076	0.023	0.014	0.887	0.318	0.247	0.075
	3	0.108	0.069	0.028	0.024	0.928	0.538	0.245	0.079
	4	0.097	0.091	0.019	0.011	1.053	0.363	0.286	0.09
	Total	0.112	0.084	0.025	0.019	0.958	0.392	0.239	0.082

* indicates that for statistical analysis the data was transformed using natural log

The MANOVA identified, a significant multivariate main effect for age-band, but no significant differences were observed between groups or for the group by age-band interaction (Table 6.25).

Table 6.25: MANOVA summary of eccentric variables.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.028	4	113	0.822	0.514	0.028
Age-band [†]	0.175	12	345	1.785	0.049	0.058
Group by age-band	0.173	12	345	1.761	0.053	0.058

[†] Indicates a significant univariate main effect between age-bands

The post-hoc univariate analysis, however, failed to identify any significant ($p < 0.0125$) difference for the individual dependent variables across age-bands. This may be explained by the using an adjusted alpha ($p < 0.0125$) to protect against familywise error.

6.4.2. Transition Phase

The transition is the second phase in the countermovement. The dependent variables representing the this phase in the MANOVA were instantaneous force (F_i), leg stiffness (K_{leg}), SCOM during the transition phase, duration of transition phase and duration of the knee transition. Both F_i and SCOM during the transition phase were analysed in the units of measurement and not normalised for body size. Normalisation for body size was not required because no relationship ($r_{xy}^2 < 0.50$) was found between body size and each dependent variable (see Appendix 13). In addition, to meet the assumption of normal distribution, F_i was log transformed. The descriptive statistics for the transition phase variables are listed in Table 6.26.

Table 6.26: Mean and standard deviations (SD) for the transition phase variables (where instantaneous force is Fi).

Group	Age-band	<i>Fi</i> [‡] (N*)		Leg stiffness [‡] (KN·m ⁻¹)		Displacement during transition phase (cm)		Duration of transition phase (s)		Duration of the knee transition (s)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	mean	SD
DCD	1	66.7	58.8	1.43	0.47	-2.6	1.9	0.127	0.101	0.05	0.04
	2	161.5	87.9	2.22	0.68	-2.6	1.7	0.080	0.040	0.03	0.02
	3	155.5	66.6	2.27	0.52	-3.1	1.5	0.089	0.050	0.05	0.04
	4	255.4	156.4	3.07	1.11	-3.0	1.6	0.083	0.040	0.04	0.02
Total		150.5	110.0	2.17	0.87	-2.8	1.6	0.096	0.067	0.04	0.03
TD	1	90.6	67.4	1.52	0.69	-2.0	1.4	0.073	0.034	0.03	0.01
	2	111.3	49.5	1.79	0.49	-3.1	1.8	0.102	0.055	0.03	0.02
	3	132.6	105.0	2.17	0.90	-3.7	1.9	0.107	0.048	0.05	0.06
	4	186.3	79.9	2.35	1.05	-3.2	1.5	0.089	0.032	0.04	0.03
Total		124.1	79.9	1.90	0.80	-3.0	1.7	0.093	0.046	0.04	0.03

* indicates that the variable was logged transformed for analysis

‡ Indicates a significant univariate main effect between age-bands

The MANOVA identified a significant main effect for age-band only. No significant differences were observed between groups and no group by age-band interaction was found (Table 6.27).

Table 6.27: MANOVA for the transition phase variables.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.059	5	112	1.397	0.231	0.059
Age-band	0.499	15	342	4.549	<0.001	0.166
Group by age-band	0.134	15	342	1.066	0.387	0.045

From the univariate analysis, *Fi* ($F(3,116) = 13.953, p < 0.008, \eta^2 = 0.265$, trend $p < 0.001$) and K_{leg} ($F(3,116) = 13.501, p < 0.008, \eta^2 = 0.259$, trend $p < 0.001$) significantly differed across age-bands. A difference of 142.6N was observed for *Fi* when

age-band 1 (78.3 ± 63.3 N) was compared to age-band 4 (220.9 ± 126.2 N). K_{leg} was also lower at age-band 1 (1.48 ± 0.58 $\text{KN}\cdot\text{m}^{-1}$) compared to age-band 4 (2.71 ± 1.12 $\text{KN}\cdot\text{m}^{-1}$).

6.4.3. Concentric Phase

The concentric phase of the countermovement is the final phase, which terminates at take-off. For the purposes of analysis, five separate MANOVAs were performed to examine the variables representing this phase. Variables were grouped as: joint ranges of motion; segmental ranges of motion; absolute joint reversals; relative joint reversals; and delay between adjacent joint reversals.

6.4.3.1. Joint and Segmental Ranges of Motion

The descriptive statistics for joint ranges of motion during the concentric phase at the hip, knee and ankle are listed in Table 6.28. These dependent variables were grouped to represent the joint ranges of motion from low point to take-off. The elbow range of motion was removed from the analysis due to errors inherent in 2D analysis (i.e., movement outside the plane of analysis).

Table 6.28: Mean and standard deviations (SD) for joint ranges of motion (ROM).

Group	Age-band	Shoulder ROM (°)		Hip ROM (°)		Knee ROM (°)		Ankle ROM (°)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	70.2	82.8	62.0	23.7	62.9	23.0	53.1	13.1
	2	52.7	104.1	64.6	13.3	64.7	13.8	54.7	7.6
	3	96.0	104.4	68.5	13.5	67.7	15.1	51.5	23.5
	4	92.1	88.5	69.2	14.0	66.9	12.9	59.0	5.9
Total		76.4	95.4	65.7	16.8	65.4	16.7	54.2	14.7
TD	1	25.5	80.0	61.3	21.0	65.5	18.6	52.8	11.2
	2	92.6	81.8	67.1	20.6	68.2	13.5	54.9	10.1
	3	135.0	83.0	66.1	12.8	58.9	10.2	49.1	7.7
	4	79.2	92.5	74.6	23.9	71.3	11.7	57.2	6.1
Total		82.5	90.3	66.7	19.9	65.9	14.4	53.5	9.5

From the MANOVA performed, no significant main effect for group, age-band or group by age-band interaction were found for the joint ranges of motion (Table 6.29).

Table 6.29: MANOVA summary of joint ranges of motion.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.005	4	113	0.142	0.966	0.005
Age-band	0.164	12	345	1.663	0.073	0.055
Group by age-band	0.090	12	345	0.889	0.559	0.030

Descriptive statistics for the segmental ranges of motion during the concentric phase are presented in Table 6.30. The dependent variables included ranges of motion from the instant of low point to take-off for the trunk, thigh, shank and foot segments.

Table 6.30: Mean and standard deviations (SD) for segmental ranges of motion (ROM).

Group	Age-band	Trunk ROM [†] (°)		Thigh ROM (°)		Shank ROM (°)		Foot ROM (°)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	23.4	9.9	37.0	14.5	25.7	13.7	28.6	8.7
	2	26.2	6.8	38.4	9.2	26.2	6.4	28.6	6.0
	3	28.1	7.8	40.6	7.9	26.9	9.6	30.4	6.7
	4	30.5	8.4	38.7	8.2	28.2	6.1	21.6	29.2
	Total	26.7	8.5	38.7	10.3	26.6	9.5	27.9	13.8
TD	1	21.3	9.7	40.0	13.0	25.8	8.3	27.1	7.1
	2	27.3	13.2	41.0	10.7	26.8	5.6	26.8	12.9
	3	29.3	10.3	35.6	6.9	23.3	6.4	25.9	6.5
	4	33.2	16.8	40.8	8.4	29.9	5.3	27.2	5.8
	Total	27.2	12.9	39.5	10.3	26.3	6.7	26.8	9.1

[†] Indicates a significant univariate main effect between age-bands

From the MANOVA performed, the only significant multivariate main effect found was across age-bands (Table 6.31). No significant main effects were found for group or group by age-band interactions.

Table 6.31: MANOVA summary of segmental ranges of motion.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.003	4	113	3.394	0.984	0.003
Age-band	0.176	12	345	5.359	0.042	0.060
Group by age-band	0.081	12	345	2.609	0.657	0.027

From the univariate analysis, the trunk range of motion was the only variable to show a difference across age-bands, ($F(3,116) = 3.897$, $p < 0.0125$, $\eta^2 = 0.092$, trend $p = 0.001$). A difference of 9.4° was found when comparing age-band 1 ($22.4 \pm 9.7^\circ$) with age-band 4 ($31.8 \pm 13.0^\circ$).

The stick figures shown in Figure 6.9 were derived using ensemble averaging with the Peak Motus software. They represent the average joint and segmental motion, starting from the instant of low point through to take-off performed by DCD and TD groups. The similarities in the movement depicted, serve to confirm visually, the lack of difference found between groups in the joint and segmental orientations, and their ranges of motion during the concentric phase.

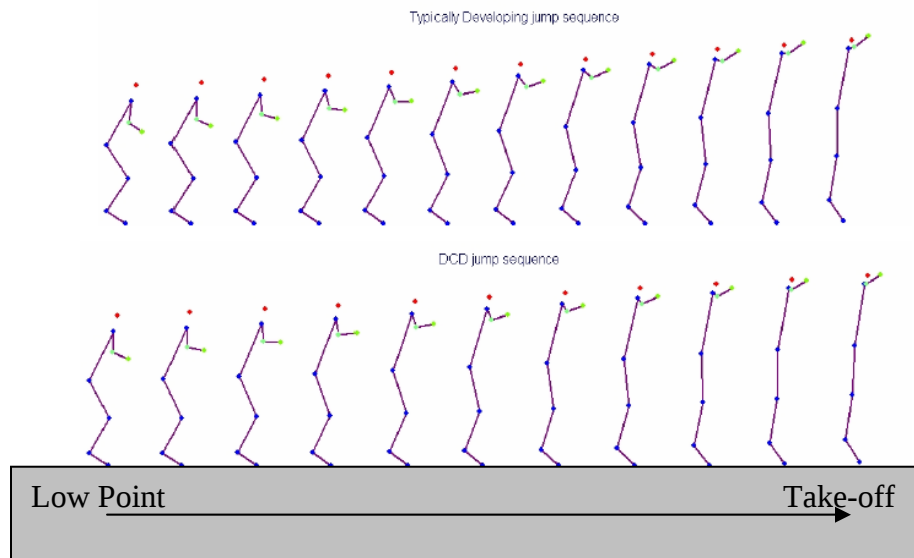


Figure 6.9: Ensemble averages for joint and segmental orientations from the instant of low point of the countermovement through to take-off.

6.4.3.2. Joint Reversals

The descriptive statistics for the dependent variables shoulder, hip, knee and ankle joint absolute reversals are listed in Table 6.32. These variables were grouped to represent the timing of reversals during the concentric phase.

Table 6.32: Mean and standard deviations (SD) for the absolute joint reversals.

Group	Age-band	Shoulder absolute joint reversal (s)		Hip absolute joint reversal (s)		Knee absolute joint reversal (s)		Ankle absolute joint reversal (s)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	-0.37	0.26	-0.29	0.09	-0.26	0.09	-0.24	0.09
	2	-0.24	0.16	-0.25	0.05	-0.20	0.05	-0.21	0.05
	3	-0.38	0.10	-0.29	0.06	-0.24	0.06	-0.23	0.06
	4	-0.38	0.17	-0.27	0.05	-0.23	0.04	-0.24	0.05
	Total	-0.34	0.19	-0.28	0.07	-0.23	0.06	-0.23	0.07
TD	1	-0.30	0.17	-0.25	0.06	-0.21	0.04	-0.21	0.06
	2	-0.34	0.13	-0.28	0.06	-0.22	0.05	-0.22	0.04
	3	-0.39	0.07	-0.28	0.06	-0.21	0.03	-0.25	0.09
	4	-0.41	0.10	-0.31	0.09	-0.27	0.07	-0.28	0.08
	Total	-0.35	0.13	-0.28	0.07	-0.22	0.05	-0.24	0.07

MANOVA identified, a significant main effect for age-band, (Table 6.33). From the univariate analysis, however, no significant differences for any of the individual dependent variables were found. In most cases, the order of joint reversal occurred from top to bottom sequence. The shoulder joint reversal was first (TD = -0.35 ± 0.13 s; DCD = -0.34 ± 0.19 s) followed by the hip (TD = -0.28 ± 0.07 s; DCD = -0.28 ± 0.07 s) and finally with the knee (TD = -0.22 ± 0.05 s; DCD = -0.23 ± 0.06 s) together with ankle (TD = -0.24 ± 0.07 s; DCD = -0.23 ± 0.07 s).

Table 6.33: MANOVA summary of absolute joint reversals.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.039	4	113	1.157	0.333	0.039
Age-band	0.176	12	345	1.793	0.048	0.059
Group by age-band	0.144	12	345	1.451	0.141	0.048

The descriptive statistics for shoulder, hip, knee and ankle joint relative reversals are listed in Table 6.34. All variables were log transformed to meet the assumptions of normal distribution for MANOVA analysis, but are reported here in their original format (percent of jump cycle) for ease of interpretation.

Table 6.34: Mean and standard deviations (SD) for relative joint reversals.

Group	Age-band	Shoulder relative joint reversal (%)*		Hip relative joint reversal (%)*		Knee relative joint reversal (%)*		Ankle Relative joint reversal (%)*	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
DCD	1	33.2	25.4	45.0	12.9	51.5	12.2	52.3	19.9
	2	36.0	41.6	38.7	8.6	49.3	8.3	46.7	11.5
	3	21.2	11.7	40.1	11.3	50.3	9.7	50.6	13.6
	4	12.5	31.5	36.3	10.9	45.8	10.5	44.0	11.1
	Total	27.0	30.0	40.4	11.2	49.5	10.2	48.8	14.7
TD	1	27.2	33.6	38.4	6.1	47.8	9.3	48.1	9.5
	2	24.5	25.6	40.3	10.7	53.7	8.5	51.8	11.0
	3	13.9	22.3	40.9	6.4	53.5	11.3	46.5	10.3
	4	24.2	6.9	43.1	6.2	51.1	5.3	49.0	9.3
	Total	22.7	25.1	40.4	8.0	51.7	9.1	49.1	10.1

* indicates that for statistical analysis the data was transformed using natural log

From the MANOVA, no significant main effects were found, (Table 6.35). For most cases, relative joint reversals occurred in the following order, shoulder ($24.9 \pm 27.6\%$ of jump cycle), hip ($40 \pm 10\%$ of jump cycle), and both ankle ($49 \pm 13\%$ of jump cycle) and knee ($51 \pm 10\%$ of jump cycle) together.

Table 6.35: MANOVA summary of relative joint reversals.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.057	4	113	1.700	0.155	0.057
Age-band	0.133	12	345	1.333	0.198	0.044
Group by age-band	0.112	12	345	1.118	0.344	0.037

The descriptive statistics for the delay between H – K and K – A reversals are listed in Table 6.36. These dependent variables represented the timing between adjacent joints. These data were log transformed to meet the assumption of normal distribution for MANOVA analysis.

Table 6.36: Mean and standard deviations (SD) for absolute delays between adjacent joint reversals.

Group	Age-band	Delay hip-knee joint reversals (s)*		Delay knee-ankle joint reversals (s)*	
		Mean	SD	Mean	SD
DCD	1	0.03	0.04	-0.01	0.06
	2	0.04	0.04	0.01	0.06
	3	0.05	0.02	-0.01	0.04
	4	0.04	0.04	0.01	0.04
	Total	0.04	0.03	0.00	0.05
TD	1	0.04	0.03	0.00	0.03
	2	0.06	0.04	0.01	0.04
	3	0.07	0.06	0.04	0.09
	4	0.05	0.03	0.01	0.04
	Total	0.06	0.04	0.02	0.06

* indicates that for statistical analysis the data was log transformed

From the MANOVA, performed, no significant main effects were found, (Table 6.37). Overall the joint reversal occurred at the hip 0.05 ± 0.04 s before the knee, and the joint reversal occurred at the knee 0.01 ± 0.05 s before the ankle. These results suggest that some individuals from the sample may not have followed the expected proximal to distal sequencing and this will be further examined in the discussion.

Table 6.37: MANOVA summary of the delay between adjacent joint reversals.

Source of variance	Pillai's trace	Hyp df	Error df	Multivariate <i>F</i>	<i>p</i>	eta ²
Group	0.037	2	115	2.181	0.118	0.037
Age-band	0.061	6	232	1.212	0.301	0.030
Group by age-band	0.052	6	232	1.029	0.407	0.026

In summary, the null hypothesis that no group difference in counter movement would be found was accepted. No differences were found in all variables from the three phases (eccentric, transition and concentric phases) of the counter movement.

CHAPTER VII

DISCUSSION

This study used kinetic and 2D-kinematic data analyses to compare the performance of the fundamental movement pattern of vertical jumping by groups of TD and DCD children. The total impairment score from the M-ABC (Henderson & Sugden, 1992) was used for the purposes of classifying children into those identified with DCD (<15th percentile) and children considered as TD (>15th percentile) at four age-bands – 5-6 years; 7-8 years; 9-10 years; and 11-12 years. Based on the derived kinetic and kinematic variables a conceptual framework was developed for the enquiry, which provided the basis for presentation of the results and the following discussion of the findings.

7.1. Differences in Jump Height

The TD group jumped significantly higher than the group identified with DCD as found in previous work (e.g., Deconinck et al., 2005; Hammond & Dickson, 1994). Overall, the group differences in jump height were relatively small. There was a considerable overlap ($\eta^2 < 0.1$) in motor ability between the groups as shown in Figure 6.1. This may be explained by a number of factors, such as:

- DCD represents a relatively mild impairment compared to those with more severe neurological problems such as Spina Bifida (Mandich, et al., 2003);

- the conceptualisation of DCD, as embracing a wide range of disabilities specific to the individual. (Consequently, some children from the DCD group jumped as well as their TD counterparts, although, in other items of the M-ABC, such as manual dexterity, they could have scored very poorly. This confirms the value of identifying more specific sub-groups of disability rather than using such a broad based generic label (e.g., Geuze, 2003));
- the DCD children in this study had persisted with physical activity despite their motor difficulties, and in this process will have of necessity, developed a sub-optimal strategy to cope (e.g., Cousins & Smyth, 2003; Henderson et al., 1992); and
- on the other hand, some children from the TD group may have chosen to live less active lives for other reasons and had not taken part in a great deal of physical activity; therefore, jumping will not have been well practiced by some of this group.

Based on previous developmental literature specific to vertical jumping, it had been decided not to analyse groups according to gender, as this variable would be unlikely to affect jump height (e.g., Malina et al., 2004). However, a post-hoc analysis of the jump height data did reveal a relationship between age-band and jump height that was gender specific (Figure 7.1). It was noted that in the DCD males < 1% of the variance found in jump height could be accounted for by age-band, in contrast to the TD males where it

was 24%. This was not replicated for the female groups, as shown in the Figure 7.1, where similar differences in jump height were found across all the age-bands. The failure of the scores of the males in the DCD group to improve with age may reflect an avoidance of activity over time, perhaps associated with the social pressure for boys to be good at sports (e.g., Bar-Or & Rowland, 2004; Cairney et al., 2006; Cousins & Smyth, 2003). Another possible explanation may simply be delayed maturation. However, a combination of these environmental and biological factors is more likely (Thomas & French, 1985).

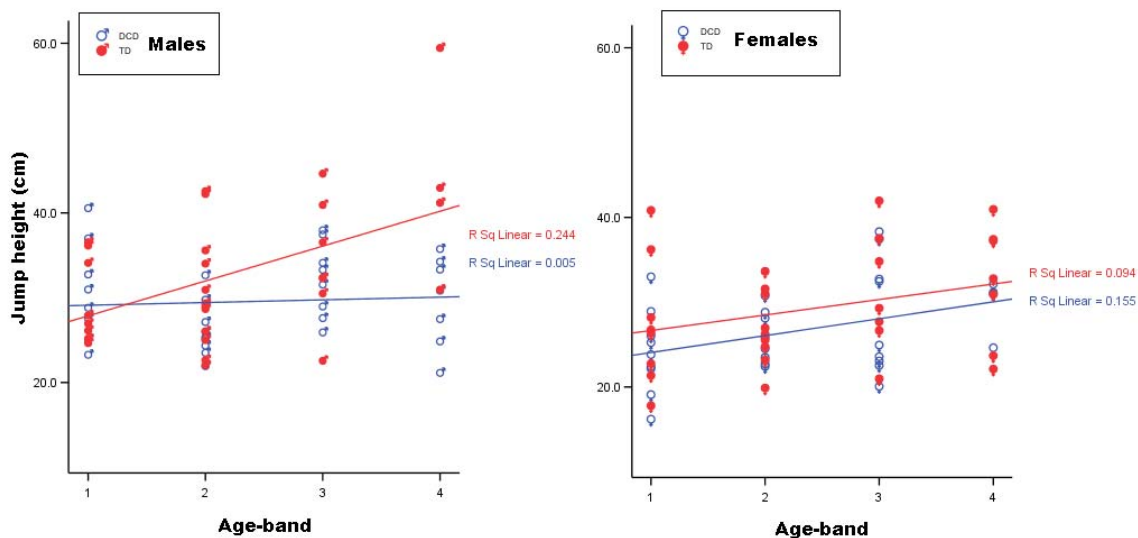


Figure 7.1: Jump height (cm) across the age-bands for male and DCD and TD groups.

Any avoidance of physical activity by children means they do not experience the stimuli required to develop expected levels of physical fitness and motor proficiency (e.g. Bar-Or & Rowland, 2004). The lack of such stimuli at an important developmental stage (e.g., 5 - 8 years of age) for muscular strength and motor performance (Malina et al., 2004), is a factor that may inhibit future development. The fact that in the male DCD children age-band did not explain jump height is consistent with the notion of physical activity

avoidance (e.g., Cairney et al., 2006). Coordination, control and strength developed through practice and experience are the likely factors that influence jump height rather than growth alone, and this was confirmed by the lack of a relationship between stature and jump height found for both groups (TD, $r_{xy}^2 = 0.09$; DCD, $r_{xy}^2 = 0.02$). Future research should seek to confirm these findings before going on to explore such explanations.

Having rejected the first null hypothesis that a group difference would be found for jump height, the conceptual framework for the enquiry will now be used to analyse the mechanisms that underpin this difference in jump performance. Specifically the centre of mass displacement during the jumping movement; the velocity, force and power variables, and the countermovement will be reviewed.

7.2. Centre of Mass Displacement

Past research on jumping has suggested that a less extended position at take-off would be observed in the DCD group compared to that adopted by the TD group (e.g., Larkin & Hoare, 1991; Meyers et al., 1977 cited by Gallahue & Ozmun, 2002). However, this was not supported by these findings as no significant group differences for the COM position at take-off, nor the joint and segmental angles at the same point were found. Essentially, take-off occurred with no differences between the groups. This meant that the TD group must have jumped higher because they created the more favourable conditions leading up to take-off. As indicated in the conceptual framework for jumping, these favourable

conditions are reflected in the VCOM, force and power variables created during the countermovement.

7.3. Velocity, Force and Power

7.3.1. Velocity of the Body's Centre of Mass and the Individual Joints and Segments,

Both peak VCOM and VCOM at take-off were significantly lower in the DCD group. This is consistent with previous research, where DCD children have exhibited slower, less explosive movements than TD children (Henderson, et al, 1992; Hoare & Larkin, 1992; Johnston et al., 2002; Raynor, 1998). Of particular significance for the understanding of coordination differences between TD and DCD groups was the finding that peak VCOM occurred earlier in the jumping movement in the DCD group when compared to the TD group. This longer elapsed time from the instant of peak VCOM to take-off, may be attributed to coordination error (Falk et al., 1997; Haguenaer et al., 2005).

Peak VCOM cannot occur at the exact instant of take-off, due to the geometric problem that is inherent in the transformation from segmental rotation to linear translation of the centre of mass (Bobbert & van Soest, 2001). In addition, when approaching take-off the lower limb joints (hip, knee and ankle) extend toward their physical limits (full extension), and antagonist activation reduces the joint velocities to minimise the risk of soft tissue damage (e.g., Siff, 2000). The well coordinated jump permits the instant of peak VCOM to occur closer to take-off and a more efficient jump performance is then

produced. Notably, 0.030 ± 0.006 s has been reported as the duration of time elapsed from peak VCOM to take-off for four different jumping protocols (e.g., Harman et al., 1990). This same time (0.030 ± 0.005 s) was replicated by the TD group in the present study. This consistency in the time elapsed from peak VCOM to take-off supports the view that for TD children, the efficient coordination of jumping is set at five years and onwards (e.g., Jensen et al., 1994). On the other hand, with the DCD group the findings of an earlier occurrence of peak VCOM suggests that a disturbance in the coordination of the movement is happening. Moreover, within the DCD group, five children identified as outliers from the box plot (for details refer back to Figure 6.3), were identified with even earlier occurrence of peak VCOM. They jumped well below the expected jump height for their age-band. Four achieved a jump height score below the 10th percentile for their age-band. This finding supports the importance of the role of coordination within the jump performance, which has been generally overlooked when TD children and adult populations are assessed (e.g., Aragón-Vargas & Gross, 1997a; Hammond & Dickson, 1994).

The effect of an earlier occurrence of peak VCOM in the jump cycle was further examined by calculating the efficiency of each jump. Efficiency was measured by the VCOM lost between the peak VCOM value and that at take-off, expressed as a percentage of peak VCOM (Figure 7.2, also see Appendix 14). Using this measure, it was found that the jumps performed by the DCD group were significantly less ($p = 0.005$) efficient than those by the TD group.

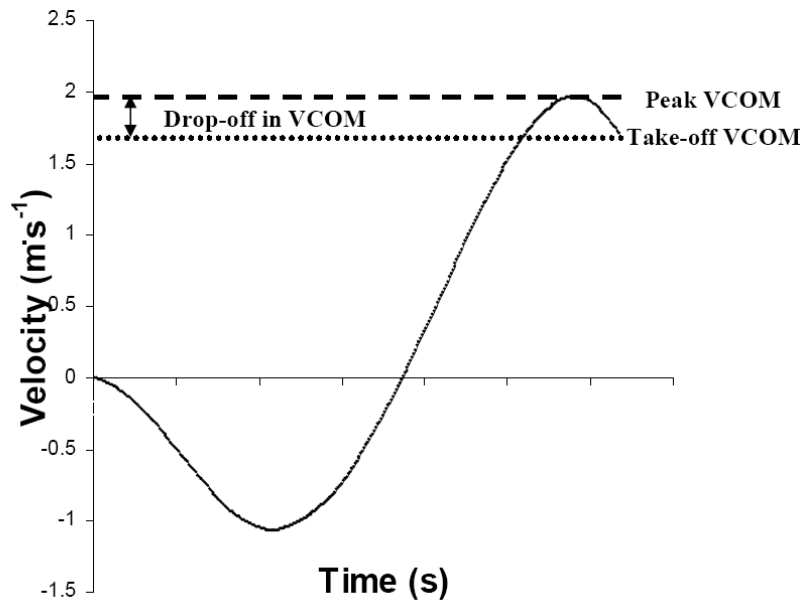


Figure 7.2: The vertical velocity of the body's centre of mass (VCOM).

The VCOM variables were derived from kinetic data, which has permitted the evaluation of coordination at a 'global' (whole body) level. Data derived from the kinematic analysis of the jump allows investigation at a more 'local' level. From all the individual joint and segmental angular velocity variables analysed, only the shank angular velocity at take-off was significantly different ($p < 0.0125$) between the groups. The TD groups' shank angular velocity was greater and in the opposing (anti-clockwise) direction to that of the DCD group (clockwise). By convention, anti-clockwise is taken as the positive direction for angular velocity (Figure 7.3). This suggests a prevailing difficulty in the coordination of the jump by the DCD group at the distal end, which may have resulted in a relatively passive or late anterior (forward) movement of the knee relative to the ankle position, giving the shank its negative low angular velocity at take-off.



Figure 7.3: Shows the difference in the direction of the shank angular velocity at take-off between typically developing group (red arrow) and DCD group (blue arrow).

Effective energy release before take-off occurs when joint angular velocities reach their peaks in a proximal to distal sequence (Bobbert & van Ingen Schenau, 1988). No significant group differences were found for the hip, knee and ankle velocity reversals (the instant of peak joint angular velocity) or the time taken between adjacent joints. This is consistent with previous reports that these variables are stable in TD children from as early as three years of age (e.g., Clark et al., 1989; Jensen et al., 1994). Furthermore, with no differences between TD and DCD groups found in the joint and segmental orientations at low point and take-off, and no differences in the countermovement variables, it can be suggested that the movement both started and finished similarly, but a

disturbed coordination of the movement by the DCD group was exhibited. This disturbance possibly resulted in the shank reaching its final position at take-off prematurely. As a result, the shank angular velocity was reduced, preventing overshooting (going beyond the desired position), minimising the translation of the shank segment to vertical velocity (Bobbert & van Soest, 2001) and giving the movement a 'jerk-like' appearance ('Jerk-like' actions during motor performance, such as running, have previously been described in children with DCD (Smyth, 1992)). To confirm these proposed explanations EMG data would be required to show specific muscle activation times.

From a neurological perspective, this dysfunction might be interpreted as an indicator of cerebellum impairment. Sub-optimal cerebellum function may affect the development of autonomous control and contribute to the movement problems children with DCD exhibit (Geuze, 2003). In this study, there was, however, no difference found between groups for any joint and velocity reversals, and therefore, no evidence of poor movement initiation. The disruption in the movement occurred later in the movement following the initiation of the concentric phase and before take-off (desired final orientation). A motor control perspective, however, appears to provide a better explanation of the data, suggesting that the disturbance of information transmission within the motor control system occurred between movement plan specification and movement realisation (Bullock & Contreras-Vidal, 1993).

The same issue with the shank has been indirectly described (but not quantified), in previous research with young non-impaired children who display an immature jumping pattern (Clark et al., 1989). It was noted, that to achieve lift off the knees were moved forward in preparation to bring the legs upward. This movement created the sensation of flight; as the feet flick upward toward the body. However, the SCOM was lower than in a typical jump as the vertical displacement of the trunk, head and arms (a greater mass than the legs) was minimal.

The proximal to distal sequencing of joint velocities, commonly described in the literature (e.g., Bobbert & van Ingen Schenau, 1988) was not found in this study. Both groups displayed hip, knee and ankle absolute peak velocities that occurred almost simultaneously. The mean time difference, between adjacent joints was no more than 0.02 s. Previous research in jumping with children has also reported no differences in hip, knee and ankle joint velocity reversals between good and poor jumpers (Jensen et al., 1994) and children from the age of three years upwards (Clark et al., 1989). Consistent with the findings of this study, between adjacent joints, velocity reversals occurred in a time of less than 0.03 s (Clark et al., 1989; Jensen et al., 1994). It is important to note, however, that a major limitation of many extant video analyses is found in the sample rate used. Common sample rates are 50 – 60 Hz and Jensen et al. used 32 Hz. These sample rates are too low to detect differences in joint and velocity reversals. Essentially, if the sample rate is too low, differences in joint timing will be missed. For example, the largest difference in peak velocity reversal was 0.03 s in this study with a sample rate of 0.02 s (50 Hz), potentially, error in these data could be around ± 0.02 s. Future work

should employ sample rates of greater than 0.005 s using high-speed cameras (i.e., over 200 Hz).

In summary, significant differences were found between the TD and DCD groups for VCOM at take-off, peak VCOM, and the timing of peak VCOM. In particular, an earlier occurrence of peak VCOM exhibited in the DCD group produced a less efficient jump and evidenced coordination difficulties. At a localised level (body part), the only difference between the groups for angular velocity at take-off was found at the shank. This difference in shank angular velocity resulted in a limited contribution to VCOM (linear) at take-off via translation in the DCD group.

7.3.2. Force and Power Output

Greater jump impulse normalised for body weight was found in the TD group. This finding was expected, given that vertical jumping is dependent upon VGRF actively developed during the concentric phase (e.g., Dowling & Vamos, 1993). Jump impulse is generally assumed to be directly related to VCOM at take-off (Dowling & Vamos, 1993; Hatze, 1998; Winter & MacLaren, 2001). The current findings would suggest that particularly for children, this assumption was a better ‘fit’ for those who were TD rather than those identified with DCD. The relationship between normalised jump impulse and VCOM at take-off was $r_{xy} = 0.761$, $r_{xy}^2 = 0.579$, $p < 0.01$ for the TD group, compared to $r_{xy} = 0.714$, $r_{xy}^2 = 0.510$, $p < 0.01$ for the DCD group. This lower coefficient of determination may be taken as further evidence that a less efficient coordination was in

some (but not all) of the children in the DCD group. Those DCD children with notable coordination disturbances were identified as outliers.

Despite the between group difference in normalised jump impulse, no differences were found for the magnitudes of VGRF. Peak VGRF is generally used as a measure of strength (Zatsiorsky, 1995) and previous research, which assessed peak force under various conditions, has supported an expectation of lower values in DCD children (O’Beirne et al., 1994; Raynor, 2001). For example, measured under isokinetic conditions, less peak torque was produced by DCD children when compared to controls (Raynor, 2001). However, this was determined from an open chain, single joint extension/flexion task, which was an isolated joint action that did not challenge balance and control. Such results would therefore not be confounded by the coordination difficulties associated with DCD. The task in this study involved greater challenges to balance and control, and the expectation was that group differences in peak VGRF would more likely be found with tasks involving movements that require whole body balance (Raynor, 2001).

The findings from this study, suggest that peak VGRF may not be as important a measure of vertical jump performance, as in squat jumps, where the concentric phase only is performed (Kolloias et al., 2001). This can be explained by the vertical jump being a less constrained movement, which allows the eccentric phase to be self-organised to take advantage of the individual’s physical characteristics. This self-organised eccentric phase, allows some ‘tuning’ of the coordination of the movement. For example, to

compensate for a lack in explosive strength, the depth of the countermovement can be increased, enabling the time period of VGRF to be applied to be extended (Bobbert et al., 1996), thus increasing jump impulse (Winter & MacLaren, 2001).

No significant group differences in this study were found for normalised HGRF magnitudes. Evidence of horizontal displacement, caused by falling forward, loss of balance, poor control or insufficient strength has been previously suggested for DCD children (e.g., Larkin & Hoare, 1991). The nature of vertical jumping requires horizontal displacement to be minimised. Therefore, HGRF is typically omitted from analyses with studies involving well coordinated (highly skilled) participants (Hatze, 1998). In this study, evidence for such unwanted movements would also have been exhibited in joint and segmental orientations at both low point and take-off, which, as discussed earlier, was not the case.

Normalised peak power was significantly greater in the TD group, in particular the largest difference between groups was found at age-band 3. Since power is the product of force by velocity, the group difference in peak power suggests that the TD group applied a peak VGRF no different to the DCD group, but at a higher velocity (Falk et al., 1997). This ability to apply VGRF at higher velocities found in the TD group is beneficial to play and sporting actions (Zatsiorsky, 1995). It requires specific physical adaptations to the muscle and tendons acquired from practice of physical activities at high intensity. From the literature it is well known that TD children participate in more high intensity activities and for longer, compared to impaired children (Stratton & Armstrong, 1991).

Hence, an assumed greater exposure over time to such activity may explain the greater peak power output found in the TD group and differences at age-band 3.

The timing of peak VGRF, peak power and low point were no different for TD and DCD groups. The eccentric phase ended at $49 \pm 6\%$; peak VGRF occurred at $67 \pm 12\%$ and the instant of peak power occurred at $84 \pm 5\%$ of the jump cycle. It has been proposed that differences in co-activation of the leg muscles, increasing K_{leg} , affect the time to build up force (Raynor, 1998; 2001). This was not supported in the present study, as no group differences were found for K_{leg} . Of interest is the evidence for differences in movement time previously reported for horizontal jumps (Deconinck et al, 2005). Jumping for horizontal distance requires an initial controlled forward rotation before the joint reversals occur. The increased task demand for trunk control during the initial forward rotation in horizontal jumping, would explain the less time to low point previously found in DCD children. Unable to replicate the same control of the trunk segment, the DCD children drop into the crouch (i.e., low point) by flexing the lower limbs, at a faster velocity than their TD counterparts. In the case of the vertical jump, the reduced balance control needed in this task can explain the lack of group differences found in the timing of low point, peak VGRF and peak power.

When time constraints are placed on a task, as found in a squat jump, group differences in performance and movement execution will be exacerbated (e.g. Schellenkens et al., 1983). However, squat jumps are less practised and have been found to be highly variable

even in TD children (Harrison & Gaffney, 2001). It was for these reasons that squat jumps were not employed in this study.

7.4. Countermovement

The results show that both TD and DCD groups performed a similar countermovement. This was evidenced by there being no significant group differences for any dependent variable associated with the eccentric, transition or concentric phase. This finding was most unexpected, as lower strength and poor control in DCD children is well documented (e.g., Deconinck et al., 2005; Hammond & Dickson, 1994; O’Beirne et al, 1994; Raynor, 1998; 2001), and has been linked with collapsing of the lower limbs during the transition phase (Larkin & Hoare, 1991). It was anticipated that the eccentric phase dependent variables would have provided evidence of this collapsing or uncontrolled lowering in the DCD group.

Differences between TD and DCD groups were also anticipated for the transition phase. As high levels of K_{leg} are synonymous with neurological soft signs such as primitive reflexes and immature balance reactions, it was expected that the DCD group would record higher measures here (Dewey & Wilson, 2001; Schoemaker et al., 1994; Geuze, 2003; Williams et al., 1983). Furthermore, high K_{leg} is associated with unskilled or novel movements (i.e., learning), and has been shown to change with training, thereby providing a more efficient movement in the form of elastic energy return (Basmajian & De Luca, 1985 ; Laffaye et al., 2005; Seyfarth et al., 1999). For this study it was assumed

that K_{leg} would be shaped by daily physical activity. Low levels of physical activity, associated with DCD children (e.g., Mandich et al., 2003; Hay et al., 2004) would reduce the child's exposure to the jumping movement, therefore compared to the TD group, the DCD group jumping would be less practiced and display an elevated K_{leg} . This assumption was, however, based on previous research, and the assessment of the physical activity of this sample was beyond the scope of this study.

This previous research that found that muscle co-activation was exacerbated in the DCD group when movement velocity was increased, used isokinetic assessments (Raynor, 2001). The use of isokinetic assessments was justified by Raynor, because they may remove balance demands (Raynor, 2001). However, isokinetic tasks are also 'novel' and unpractised movements (i.e., constant velocity throughout the whole range of motion), and require considerable practice for reliable results (e.g., Brown & Weir, 2001). (Raynor's study did not report test reliability for the EMG measures used or include a familiarisation protocol in the method). As such, the group differences reported may have been caused by the greater difficulties DCD children have in performing novel or unlearned tasks (Hands & Larkin, 2002; Larkin & Hoare, 1991; Parker & Larkin, 2003). Based on this assumption, the lack of group differences found in this study for K_{leg} may then be explained by the greater familiarity of the jumping task used.

An alternative task related explanation for the lack of difference found between TD and DCD groups in K_{leg} is that this task is dependent upon force actively developed during the concentric phase and less on the utilisation of stored elastic energy (Kubo et al.,

1999). If a more intense SSC task was used, such as depth jumping, where stored elastic energy predominates, this would be highly dependent upon K_{leg} and the measures would have been more distinguishable (e.g., Laffaye et al., 2005; Seyfarth et al., 1999). Further support for this explanation can be found in K_{leg} values of between 12 - 16 kN.m⁻¹ being reported for running and long jump tasks (Farely & Gonzalez, 1996; Seyfarth et al., 1999), far greater than the K_{leg} values presented in this study.

A further analysis of the DCD group data was undertaken, which examined the difference in K_{leg} for those who had difficulties in dynamic balance and those who didn't. For the analysis, the DCD group was divided into two sub-groups; those who scored zero for the dynamic balance items (DCD-DB0, $n = 29$) and those who scored one or above (DCD-DB1+, $n = 33$). A difference was found between DCD-DB0 and DCD-DB1+, ($F(1,54) = 9.126$, $p = 0.004$, $\eta^2 = 0.145$) and across age-bands ($F(3,54) = 5.997$, $p = 0.001$, $\eta^2 = 0.250$). Mass and K_{leg} showed a linear relationship for both groups (DCD-DB0, $r_{xy}^2 = 0.431$; DCD-DB1+, $r_{xy}^2 = 0.455$), and stature and mass were highly correlated (DCD-DB0, $r_{xy}^2 = 0.826$; DCD-DB1+, $r_{xy}^2 = 0.736$). Therefore, mass only was used as a covariate in a 2 x 4 ANCOVA. From the results, mass was found to have a significant effect ($F(1,53) = 12.460$, $p = 0.001$, $\eta^2 = 0.190$). The significant difference between DCD-DB0 and DCD-DB1+ remained when the effect of mass was accounted for ($F(1,53) = 4.814$, $p = 0.033$, $\eta^2 = 0.083$), but across the age-bands the significant difference was removed ($F(3,53) = 2.591$, $p = 0.062$, $\eta^2 = 0.128$). Adding mass as a covariate increased the explained variance from 49.8% to 59.3%, thus, improving the statistical power of the ANOVA model. This finding supports the notion that excessive

muscle co-activation during the transition of joint reversals, represented by K_{leg} , provides at least a partial explanation for the dynamic balance difficulties experienced by some of the DCD children.

No differences between TD and DCD groups for the concentric phase were found. These variables included the SCOM, joint and segmental flexion at the low point, their range of motion from low point through to take-off and measures of coordination (joint reversals). In addition, no significant differences between TD and DCD groups for absolute and relative joint reversals were found. These measures failed to identify coordination differences between the two groups. The values for the absolute hip joint reversals (TD = -0.28 ± 0.07 s; DCD = -0.28 ± 0.07 s) in this study were similar to those (0.24 – 0.28 s) reported by Jensen et al. (1994).

A single optimal solution for jumping that involves joint reversals that follow a proximal to distal sequence, has been suggested based on group data and mathematical simulations (e.g., Bobbert & van Soest, 2001). However, neither of the groups followed this expected knee to ankle joint reversal sequence commonly reported in the literature. Some evidence suggesting that the distinction between knee - ankle reversals is less clear, has emerged from previous studies when individual participant data were analysed (Aragón-Vargas & Gross, 1997b; Vanezis & Lees, 2005). For example, two of the three adults assessed over 50 jumps performed best when they used a hip-ankle-knee sequence of coordination (Aragón-Vargas & Gross, 1997b). More recently, ankle - knee sequencing in some (but not all) participants were identified, but masked in group data (Vanezis & Lees, 2005).

Therefore, important information about sequencing of joint actions may be lost when group data are analysed.

7.5. Group Differences by Age-band

Multivariate main effects were found for the age-band comparisons. Children in the older group, jumped higher, and utilised a deeper countermovement, but, showed no differences in joint or segmental angles to those in other age-bands at low point and take-off. Given that children between 5 and 12 years are growing and developing, it was assumed that differences exhibited across age-bands were a function of stature and related physical characteristics, rather than different control strategies. However, this assumption may need to be further examined given that the relationships between stature and all SCOM variables were all $r_{xy} < 0.80$ (see Appendix 13) and normalised jump impulse peak power and average power, were all significantly different across age-bands.

Peak VCOM and VCOM at take-off were also significantly different across age-bands. However, most importantly, no difference across age-bands was found for the time elapsed from peak VCOM to take-off. This data were obtained from a cross-sectional study and require confirmation from longitudinal evidence. The information gained from longitudinal studies may give more insight into the underlying factors causing the group difference. If with age, improvements in the timing of peak VCOM (i.e., occurrence closer to take-off) occur later this may be taken as evidence of delayed development and/or a lack of practice. However, if an earlier occurrence of peak VCOM persists with

age, an alternative explanation related to transmission of information within the motor control system may be necessary.

The range of motion of the trunk from low point to take-off was different across age-bands, providing some evidence of a change in control strategy as a function of age. This change can be explained by differences in strength and control of the trunk (Bobbert et al., 1996; Komi, 2003; Kubo et al., 1999). Increased range of motion of the trunk places higher demands on balance control, and greater energetic cost for jumping, yet it is a recognised strategy used by skilled jumpers when the task changes from sub-maximal (75% maximum) to maximal jumping. Control demands are further challenged due to growth, with increased mass and length of limbs (Gallahue & Ozman, 2002; Jensen, 1981a; b; 1986; 1987; 1988; 1989). Through practice and with advancing age, children who follow typical development get stronger and improve control of the proximal joints. These changes are reflected in greater trunk inclination during jumping (Clark, et al., 1989; Jensen et al., 1994). The knee and ankle joint orientations generally do not change with age (Clark et al., 1989).

Minimum VGRF, K_{leg} and F_i were also significantly different across age-bands, suggesting that downward acceleration of the COM during the eccentric and transition phase changed with age-band. These findings coincide with the differences in body size, strength and power output. Furthermore, normalised jump impulse, peak power and average power were all different across age-bands; this suggests that physiological factors other than physical size impacted upon these findings (Bosco & Gustafson, 1983;

Docherty, 1996). Such changes are consistent with previous findings (Davies & Young, 1984; Ferretti et al., 1994; Harrison & Gaffney, 2001).

7.6. Summary

This investigation used vertical jump analysis to better understand motor performance and movement differences between TD and DCD children aged between 5 and 12 years. Whereas previous work has been based on performance measures such as jump height and qualitative observations (e.g., Hammond & Dickson, 1994), this study approached the problem by using a more detailed biomechanical analysis of jump performance. Data were collected on site at the school involved in this study; therefore, an advantage was the children's familiarity with the surroundings as compared to the impact of 'bussing' them into a laboratory setting. This strategy, however, involved some limitations to the motion analysis, namely with the need for manual digitisation and sampling.

7.6.1. Limitations - Equipment

- At the time of the data collection, a 2D motion analysis system using video represented current technology, and high speed cameras were less accessible and more expensive. Recently, the technology has been superseded with high speed infrared 3D motion analysis becoming standard in biomechanics laboratories. Valid measures of joint moments from jumping movements, using inverse dynamics, can only be acquired from high speed 3D analysis. It is well known

that the sampling rate (50Hz) of video analysis does not provide valid acceleration data for movements such as jumping, and generally 200Hz is now currently used (e.g., Kubo et al., 2007). Hence joint moments (torque) could not be assessed.

7.6.2. Limitations - Sampling

- The study was based on a sample recruited from a single school; therefore, the generalisation of the findings to the broader population may be limited. It should be noted that, the number of children identified with DCD (30% of the sample assessed) using the M-ABC was higher than the 5-15% generally reported in the literature (e.g., Larkin & Rose, 1999). However, similar proportions of children identified with DCD were found in a recent study with a larger sample size, drawn from two primary schools in different suburbs of Melbourne, with a similar socio-economic status to that of the present study (Wilson, 2008).
- The school's motivation to partake in this study came from concern expressed by the Physical Education Department, regarding their pupils' low level of gross motor proficiency and physical fitness based on their observations during class. From the census figures (Victorian Electoral Commission, 2001), socio-economic status of the school catchment area was not low, however, the cultural background (although not formally assessed) was mixed and typical of Melbourne (See Appendix 15 for further discussion).

7.6.3. Limitations – Other

- The M-ABC used in the study to classify the experimental groups was the first edition, which has since been revised. The changes to the first edition include an expanded age-range (3 to 16 years), substantial validation work, and more task-age overlaps (Henderson & Sugden, 2007). Similarly, the BOMPT has also recently been revised (BOT-2), and reviewed by Deitz, Kartin and Kopp (2007).
- Although, similar ‘developmental’ research has been published using such experimental designs (e.g., Jensen et al., 1994), the cross-sectional design limited the inferences that can be made concerning the delayed development process.
- The post-hoc observations that jump performance was found to differ by gender, suggests that it may have been more prudent for the experimental design to have accounted for this variable, despite the findings of previous research (e.g., Malina et al., 2004).

7.7. Recommendations and Suggestions for Future Research

The following recommendations and suggestions for future research are proposed:

- The broad nature of the concept of DCD needs refining. At present the possibility of sub-groups within DCD cohorts can lead to meaningful data, such as extreme

scores becoming lost within the group means (Visser, 2003). Small effect sizes in this study were evidence for such difficulties in dealing with group mean data. Unfortunately, one assumption of MANOVA requires all outliers to be removed, when in fact those outliers are participants with the greatest impairment, unless the data have been compromised. Given this, outliers need to be taken into account in the study of DCD.

- A potentially important finding was that of no relationship between jump height and age-band in the male DCD children. This lack of a relationship should be tested by further study.
- If this gender specific lack of relationship between age-band and motor performance is confirmed, this highlights the importance of early identification and the need for subsequent intervention. Avoidance and withdrawal from physical activity will be most detrimental to the child's development.
- A key variable to emerge from the forceplate data that differentiated groups was the timing of peak VCOM relative to take-off. Further work is required to confirm the usefulness of this variable as a measure of coordination.
- For large samples, forceplate measures alone provide an adequate and effective means of assessment of vertical jumping. The forceplate method compared to video analysis: 1) provides greater sensitivity (measurement precision) to

impaired coordination because of the higher sampling rates, 2) is less time consuming and requires little participant preparation (e.g., no joint marker attachments), especially when manual digitisation of markers is used in the movement analysis.

- The lack of group differences found for K_{leg} , may be due to the characteristics of the vertical jump task employed. Future research should investigate children's ability to regulate K_{leg} under more challenging conditions, such as, different surfaces or increased task intensity. This would challenge the child's ability to adapt to changed conditions, important for 'everyday' situations. In the present study, the surface stiffness (compliance) was constant throughout the study. Changing it may give further insight into the coordination and regulation difficulties experienced under different environments and different task demands. Furthermore, the task intensity of the concentric phase in the present study was maximal, but the loading (eccentric phase) was relatively low when compared to other SSC activities. Determining how DCD children adapt their K_{leg} under such conditions will advance understanding of the disorder and help explain their difficulties in ability to accommodate challenging environments.

Given the findings and in accordance with the recommendations specific to the variables used a revised conceptual framework is presented below (Figure 7.4). The revised framework is specific to the assessment of vertical jumping and those dependent variables that failed to differentiate between TD and DCD groups have been removed.

Jump height remains as the focus of the analysis and explanatory variables provided from the velocity variables, peak power, jump impulse and leg stiffness, with most countermovement and all kinematic variables omitted, thus providing a more parsimonious explanation (although group differences were found for shank angular velocity at take-off, this variable was related to the time elapsed from peak VCOM to take-off, making it redundant).

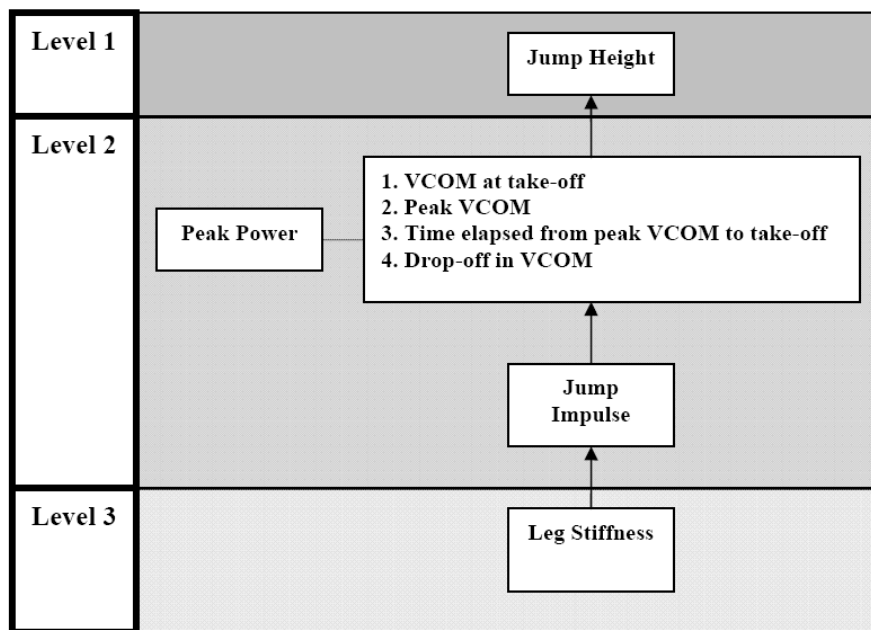


Figure 7.4: The revised conceptual framework for enquiry.

7.8. Conclusion

This study of vertical jumping confirmed that the motor performance by DCD children is below that of their TD peers. The DCD group's movement was less efficient, with a greater percentage of VCOM loss between peak VCOM and take-off. Coordination error

was identified as a probable mechanism underlying the less efficient movement exhibited by the DCD group. Kinematically, the group differences in shank angular velocity at take-off provided the evidence. Specifically, the DCD group's shank at take-off was moving (clockwise) in the opposing direction to that of the TD group (anti-clockwise). At take-off, the contribution of the shank segment to VCOM via translation was, therefore, negligible in the DCD group (Bobbert & van Soest, 2001). No evidence for placement error was found, as COM position, joint and segmental orientations at low point (initial position of the concentric phase) and take-off (desired final position) were no different. Therefore, the timing from initial to desired final position was interpreted as holding the key.

In addition to coordination error, the differences found in jump performance between TD and DCD groups were likely to reflect the 'vicious cycle' of hypoactivity that over time leads to lower fitness, a decline in health, and differences in daily physical activity. The link between low daily physical activity and DCD is well established in the literature (e.g., Cairney et al., 2006). This was supported by the findings of lower measures for normalised jump impulse, peak VCOM, take-off VCOM and normalised peak power in the DCD group. These group differences can reflect more limited exposure to practice of fundamental movements. In particular, both TD and DCD groups were able to impart similar normalised VGRF, but the DCD group did this whilst moving at a lower VCOM, which resulted in the observed lower normalised peak power. This finding reflects less exposure to high intensity exercises, such as sprinting and jumping for the DCD group (Zatsiorsky, 1995).

Acknowledging the limitations of the kinematic data previously identified, the DCD group's joint and velocity reversals were no different to those of the TD group, suggesting that the coordination required to initiate movement was intact and the disturbance occurred between the final reversal at the distal end and take-off. An explanation for this coordination error is as yet unclear. Drawing from Bernstein's framework (1967), one line of future research could be to search for evidence of the final learning stage caused by a lack of practise, as the timing of VCOM was stable in the TD group and comparable to adults from previous studies (Harman et al., 1990). However, when the data for the timing of peak VCOM were probed, participants identified as outliers due to their timing of peak VCOM scores were found at not just the youngest age-band, as expected when a delay in development or lack of practice provides the explanation, but at age-bands 1, 2 and 3. Therefore, a likely alternative explanation is that for at least some of the DCD group a disturbance in the transmission of information within the motor control system (neuromotor noise) is occurring.

7.9. Implications

This study was designed as a biomechanical analysis of jumping, however, future research would provide more explanatory insight if an expanded framework, to include other variables, were adopted. The rate and nature of change could be better analysed and the impact of physical activity more meaningfully discussed if additional variables included data derived from:

- longitudinal study of DCD and TD children, starting at a younger age, such as 3 years through to 12 years;
- measures of physical activity using a questionnaire and/or pedometer monitoring;
- a comprehensive anthropometric evaluation, including body composition and bone lengths
- psychological assessments (e.g., self-efficacy)
- nutrition intake and choice
- socio-cultural influences
- measures of physical fitness, including laboratory assessments of balance and coordination

Given these recommendations and in accordance with the findings of this study provided the expanded research framework is presented below (Figure 7.5) as one of the implications for future investigations, and particularly interventions with DCD children. This framework identifies factors which need to be accounted for as part of a movement assessment such as jumping. In turn, the socio-cultural and other environmental factors may be targeted for interventions aimed at breaking the ‘vicious cycle’ of physical activity avoidance.

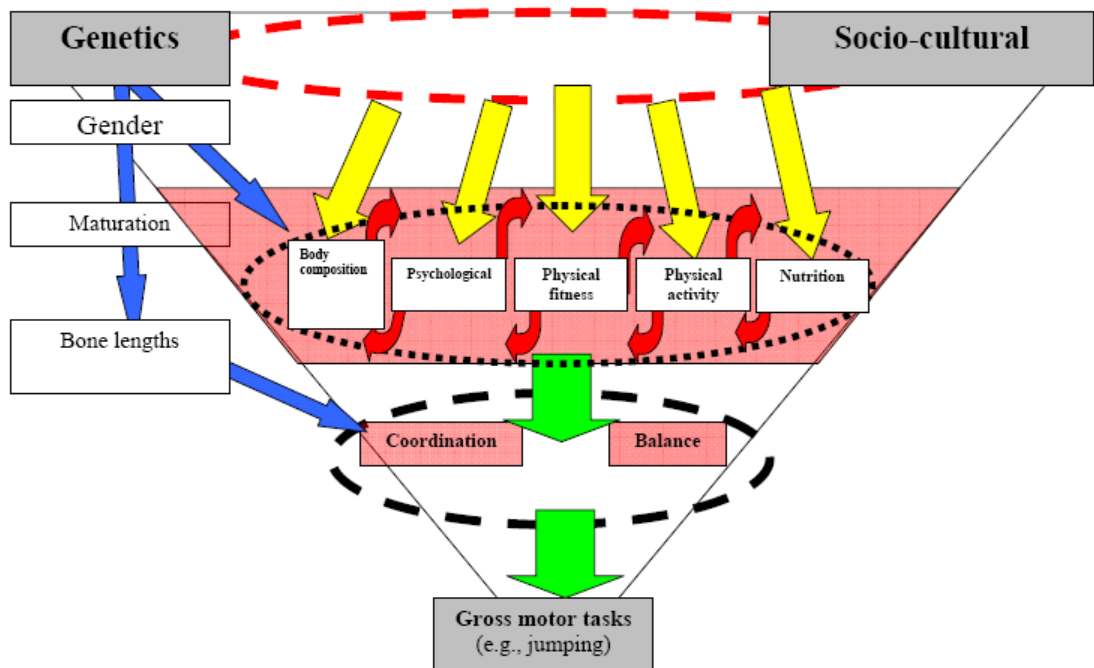


Figure 7.5: The expanded framework for future investigations and interventions with DCD children.

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APPENDICES

APPENDIX 1

Laboratory Based Normative Data for Vertical Jumping

Table A1: Laboratory based normative data for vertical jumping.

Study	Ergometer	Participants	Age (years)	Stature (cm)	Mass (kg)	Jump Type	Jump height (cm)	Power (W)	Ave power (W)	Power (W·kg ⁻¹)	Ave power (W·kg ⁻¹)	Jump Impulse (N·s)
Davies & Young (1984)	Forceplate	Girls n=4 Boys n=6	11.7±0.4 11.8±0.4	149.2±11.3 146.9±2.3	38.4±2.8 39.9±9.3	SJ	18.3±3.8**	711±292	437±165	18.2*	11.2*	68±18
Ferretti et al. (1994)	Forceplate	Boys n=13	8-13	-	-	SJ	-	1103±393	-	31.6±8.4	-	Peak force (N)
Vicente-Rodríguez et al. (2003)	Forceplate	soccer n=53 control n=51 soccer n=53 control n=51 (All boys)	9.3±0.2 9.3±0.2	135.2±1.2 137.1±1.3	31.9±0.9 35.5±1.6	SJ CMJ	16±1** 14±1** 18±1** 17±1**		160.9±6.5 160.6±7.7 223.1±10.2 232.4±11.2		5.0* 4.5* 7.0* 6.5*	356.7±12.7 392.0±13.7 394.0±14.7 427.3±18.6
Pääsuke et al., (2001)	Forceplate	Boys n=14	11.4±0.1	152.8±2.9	40.3±2.8	SJ CMJ	27±1 28±1					
Study	Ergometer	Participants	Age (years)	Stature (cm)	Mass (kg)	Jump Type	V _{cmj} @TO (m·s ⁻¹)	Jump height (cm)				
Harrison & Gaffney (2001)	Forceplate	Girls n=12 Boys n=8 Combined n=20 Girls n=12 Boys n=8 Combined n=20	6.0±0.4 6.0±0.2	-	27.0±3.0 29.0±4.0	SJ CMJ	1.36±0.23 1.40±0.19 1.37±0.21 1.44±0.19 1.57±0.23 1.49±0.21					
McKay et al., (2005)	Forceplate	Girls n=34 Boys n=36 Combined n=70	10.2±0.8 10.2±0.7 10.2±0.7	144.7±8.4 142.6±8.1 143.6±8.3	36.7±7.7 36.2±7.5 36.4±7.5	nsCMJ		22.6±5.3 25.8±5.3 24.2±5.5				

*not reported but estimated using absolute divided by mass

Adult populations												
Author	ergometer	Participants	Age (years)	Stature (cm)	Mass (kg)	Jump Type	Jump height (cm)	Power (W)	Power (W·kg ⁻¹)	Peak Force (N)	Peak Force (N·kg ⁻¹)	Jump Impulse (N·s)
Chamari et al., (2004)	Forceplate	Soccer boys n=30	17.5±1.1	177.8±6.7	70.5±6.4	SJ	51.3±6.7	3878±553	55.1±5.7	1863±262	26.5±2.7	
Pääsuke et al., (2001)	Forceplate	Boys n=14	16.4±0.1	176.5±1.7	67.8±2.5	SJ CMJ	30±1 32±1					
Seyers et al., (1999)	Forceplate	Females n= 49 Males n= 59 Combined n=108 Females n= 49 Males n= 59 Combined n=108	20.4±2.2 21.3±3.4		64.7±9.8 78.3±15.4 71.5*	SJ CMJ		2993.7±542.9 4620.3±822.48 3861.2±1076.4 3069.1±818.24 4708.4±888.9 3964.6±1183.6	46.27* 59.01* 54.00* 47.44* 60.13 55.44*			

*not reported but estimated using absolute divided by mass

Field Based Normative Data for Vertical Jumping

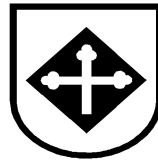
Table A2: Field based normative data for vertical jumping.

Author	Ergometer	Participants	Age (years)	Stature (cm)	Mass (kg)	Jump Type	Jump height (cm)
Bencke et al., (2002)	Contact mat	Swimming					
		Elite Boys n=9	12.0 (9.2-13.0)	153.0 (137.9-164.6)	41.7 (29.5-54.7)	SJ	26.0 (23.0-31.0)
						CMJ	27.0 (25.0-31.0)
		Elite Girls n=13	11.4 (10.0-12.9)	150.0 (141.6-164.7)	40.0 (30.0-52.2)	SJ	23.5 (17.0-28.0)
						CMJ	23.5 (17.0-29.0)
		Non-elite Boys n=20	11.8 (10.9-13.9)	154.5 (142.3-166.4)	44.8 (32.0-53.0)	SJ	22.0 (19.0-28.0)
						CMJ	23.0 (20.0-31.0)
		Non-elite Girls n=8	10.7 (10.2-11.5)	144.9 (133.3-156.8)	33.9 (25.1-51.8)	SJ	23.0 (17.0-29.0)
						CMJ	23.5 (15.0-32.0)
		Tennis					
		Elite Boys n=12	11.9 (10.5-12.7)	153.4 (139.0-168.5)	43.0 (29.4-57.9)	SJ	25.5 (19.0-29.0)
						CMJ	26.0 (21.0-36.0)
		Elite Girls n=12	11.1 (10.0-12.7)	145.9 (134.6-164.4)	37.1 (30.6-60.2)	SJ	24.5 (19.0-28.0)
						CMJ	26.5 (21.0-34.0)
		Non-elite Boys n=6	11.9 (10.0-12.2)	151.7 (148.3-164.9)	38.3 (34.4-61.3)	SJ	23.0 (22.0-26.0)
						CMJ	24.5 (22.0-27.0)
		Non-elite Girls n=7	11.7 (9.4-12.7)	155.5 (136.5-167.0)	42.0 (29.3-51.5)	SJ	23.0 (20.0-30.0)
						CMJ	24.0 (20.0-33.0)
		Handball					
		Elite Boys n=12	12.5 (11.7-12.7)	152.9 (143.5-171.2)	42.7 (33.0-52.5)	SJ	28.5 (20.0-33.0)
						CMJ	28.5 (19.0-35.0)
		Elite Girls n=12	12.0 (11.5-12.7)	152.5 (143.7-163.7)	39.8 (33.8-61.4)	SJ	23.0 (19.0-33.0)
						CMJ	25.0 (19.0-32.0)
		Non-elite Boys n=12	12.3 (11.4-12.9)	159.1 (146.6-166.1)	47.2 (38.7-53.3)	SJ	24.0 (21.0-30.0)
						CMJ	26.0 (22.0-33.0)
		Non-elite Girls n=12	12.3 (11.1-12.9)	154.9 (140.5-166.0)	45.4 (35.5-60.0)	SJ	25.0 (20.0-31.0)
						CMJ	25.0 (21.0-33.0)
		Gymnastics					
		Elite Boys n=11	11.7 (10.8-13.8)	146.2 (127.1-162.4)	35.3 (26.7-47.0)	SJ	28.0 (24.0-33.0)
						CMJ	30.0 (22.0-38.0)
		Elite Girls n=6	12.6 (10.8-12.7)	141.1 (136.9-144.3)	34.4 (32.9-46.2)	SJ	23.0 (20.0-30.0)
						CMJ	25.0 (21.0-27.0)
		Non-elite Boys n=13	11.8 (9.5-12.9)	146.1 (131.7-157.6)	37.1 (28.5-45.5)	SJ	26.0 (21.0-30.0)
						CMJ	27.0 (23.0-36.0)
		Non-elite Girls n=20	11.7 (9.4-12.9)	147.1 (128.5-161.1)	35.3 (26.0-55.2)	SJ	25.0 (18.0-31.0)
						CMJ	27.0 (19.0-35.0)
		Combined **					
		Elite Boys n=44	12.0 (9.2-13.8)	151.4 (127.1-171.2)	40.7 (26.7-57.9)	SJ	27.0 (19.0-33.0)
						CMJ	28.0 (19.0-38.0)
		Elite Girls n= 43	11.8 (10.0-12.9)	147.4 (134.6-164.7)	37.8 (30.6-61.4)	SJ	23.5 (17.0-33.0)
						CMJ	25.0 (17.0-34.0)
		Non-elite Boys n= 51	12.0 (9.5-13.9)	152.9 (131.7-166.4)	41.9 (28.5-61.3)	SJ	24.0 (19.0-26.0)
						CMJ	25.0 (20.0-36.0)
		Non-elite Girls n= 47	11.6 (9.4-12.9)	150.6 (128.5-167.0)	39.2 (25.1-60.0)	SJ	24.0 (20.0-31.0)
						CMJ	25.0 (15.0-35.0)
		Total n= 185	11.9 (9.2-13.9)	150.6 (128.5-171.2)	39.9 (25.1-61.4)	SJ	24.5 (17.0-33.0)
						CMJ	26.0 (17.0-38.0)
Bosco (1992)	Contact mat	Boys	7-17			SJ	20-32
		Girls	8-13				16-23
Doré et al. (2001)	Contact mat	Girls n=401	8-18			SJ	19
		Boys n=460	8-18				20
Diallo et al., (2001)	Contact mat	Soccer	12±0.4	153.1± 6.9	41.2±4.8	CMJ	29.2±3.9
		Boys n=10				SJ	27.3±4.0
Butterfield et al., (2004)	Vertisomic	Girls n=31	11-13			CMJ	31.3±5.5†
		Boys n=45					33.9±7.0†
		Combined n=76					32.8±6.5†

† converted to cm from inches (using 1 inch = 2.54cm)

** estimated from individual data

APPENDIX 2



AUSTRALIAN CATHOLIC UNIVERSITY

Information Letter to Participants

Dear Participant,

We are conducting a study using a vertical jump. The aim of the study is to help us to better understand the role of arm swing; its effect during a countermovement jump and the reliability of the testing procedures. Each trial will include up to 25 jumps for each condition (arm swing or no arm swing), with the emphasis on attainment of maximal height. During these trials you will be videotaped for later movement analysis. To ensure that the reference points are correctly identified, you will be dressed in dark lycra/spandex and reflective markers will be placed on the ankle, knee and other landmarks. Sufficient rest between trials will be given to reduce the effects of fatigue and ensuring a safe testing environment. The entire duration required for testing should be no longer than 60 minutes (excluding the warm-up). While all individual results will be kept confidential, descriptive statistics will be reported for the group only. The results from the study will help add to our understanding of the role and influence arm swing has on the performance of vertical jump. At any time during the project you are free to withdraw from the study.

In order to complete a reliability study, following the completion of the testing procedures (minimum 24 hours), you will be invited to return to repeat the study again. This is essential to establish reliability of the testing; in this case a subject identification number will be given to enable comparison over repeated trials. This number will only be disclosed to you and the investigators. As mentioned previously, the study will be using group mean data and therefore the individual scores will remain confidential and secured in electronic format.

If you would like to take part in this study, please fill in the attached consent form and return it to:

Dr Wayne Maschette
Australian Catholic University
School of Human Movement
115 Victoria Parade, Fitzroy, Vic 3065

Should you have any queries please contact **Dr. Wayne Maschette on (03) 9953 3041**

Please be advised that this study has been approved by the University Human Research Ethics Committee at Australian Catholic University. In the event that you have a query
or

Complaint about the way that you have been treated during the study, you may write care of the nearest branch of the Office of Research

*Chair, University Human Research Ethics Committee
C/o Office of Research
Australian Catholic University
115 Victoria Parade, Fitzroy VIC 3065
Tel: 03 9953 3157 Fax: 03 9953 3305*

Any complaint made will be treated in confidence, investigated fully and the participant informed of

the outcome. If you agree to participate in this project, please complete the details on both copies of the Informed Consent form and sign them, retain one copy for your records and return the other copy to the supervisor at the Australian Catholic University.

Thank you for your co-operation with this important research.

Yours faithfully,

Dr. Wayne Maschette, Supervisor



Australian Catholic University

Consent form :
(Copy 1 – to be retained by Participant)

Participant's Name

Date of birth

Gender

I, _____ of _____

Hereby consent to participating in the research study on vertical jump to be taken by Dr. Wayne Maschette, Mr Noel Lythgo and Mr. Morgan Williams of Australian Catholic University.

I understand that

- (a) I am free not to participate if I do not wish to do so and that I am free to withdraw at any time;
- (b) I am free to withdraw my consent at any time and withdraw any information supplied by myself;
- (c) Any videotaping of myself will only be used for assessment. It will not be shown to anyone not directly associated with the study without my express consent;
- (d) The project is for the purpose of research and is not for treatment;
- (e) Any information I supply will be confidential.

Signed _____ Date; _____
(Participant/ Guardian if under 18 years of age)

Signed _____ Date; _____
(Principal supervisor/Researcher)

Australian Catholic University Limited A.C.N. 050 192 660
St. Patrick's Campus 115 Victoria Parade, Fitzroy, Victoria 3045, Australia
Mail: Locked bag 4115 Fitzroy MDC 3065, Australia
Telephone 61 3 9953 3041 Facsimile 61 3 9953 3095



Australian Catholic University

Consent form :
(Copy 2 – to be retained by Supervisor)

Participant's Name

Date of birth

Gender

I, _____ of _____

Hereby consent to participating in the research study on vertical jump to be taken by Dr. Wayne Maschette, Mr Noel Lythgo and Mr. Morgan Williams of Australian Catholic University.

I understand that

- a. I am free not to participate if I do not wish to do so and that I am free to withdraw at any time;
- b. I am free to withdraw my consent at any time and withdraw any information supplied by myself;
- c. Any videotaping of myself will only be used for assessment. It will not be shown to anyone not directly associated with the study without express consent;
- d. The project is for the purpose of research and is not for treatment;
- e. Any information I supply will be confidential and I am aware that for the purpose of the study an identification number will be given to help collate results over repeated trials. Also, all reported data will be in the form of group descriptive statistics that does not enable identification of participants.

Signed _____ Date; _____
(Participant/ Guardian if under 18 years of age))

Signed _____ Date; _____
(Principal supervisor/Researcher)

Australian Catholic University Limited A.C.N. 050 192 660
St. Patrick's Campus 115 Victoria Parade, Fitzroy, Victoria 3045, Australia
Mail: Locked bag 4115 Fitzroy MDC 3065, Australia
Telephone 61 3 9953 3041 Facsimile 61 3 9953 3095

APPENDIX 3

Information Letter to Principals

Dear Principal,

I am writing to inform you of a research study being conducted by the School of Human Movement, Australian Catholic University. Permission has been received from Education Victoria (reference number SOS001127) and the Catholic Education Office (reference number GE99/0009) to make initial contact with Principals to explain the project and seek involvement of the School communities.

The research project focuses on motor skill proficiency in children and their ability to perform the fundamental skill of jumping. In the past, some children have been labelled “clumsy”, a term that often carries a social stigma with it. The aim of our study is to examine differences in motor development in order to better understand why some children may experience movement difficulties.

Our study will involve children aged between 5 and 12 years who will be asked to complete a number of simple movements. The type of movement examined are throwing, catching, balancing, jumping and writing. A recognised standard test kit known as the ‘Movement ABC’ will be used to assess the level of motor proficiency. The results are reported as percentile scores. For example, a child who scores lie on the 50th percentile is at a development stage where some skills are performed better than other children but not as good as some others. This will be explained to you in detail in a post test interview session by one of the researchers.

In addition to the movement ABC, a vertical jump will be performed. During this task the children will be videotaped for later movement analysis. All of the tasks are fun and safe but challenging and should take no more than about 1 hour to complete (including a short break in between).

While all individual results will be confidential, the results from the study will help develop our understanding of how children’s motor grow. Such knowledge is usually published in a scientific journal as anonymous results from a testing program. It is our intention to publish the results of this study in such a journal. At any time during the project the parent or child are free to withdraw from the study and all information returned to you or destroyed.

At the end of the study, we will welcome discussion with the parent of how well the child performed on these tasks and the child’s current level of motor development. Where there is a concern about the level of development we will make recommendations for the parent to consider.

Should you have any queries or would like to discuss any of the issues raised please contact the principal investigator, Dr Wayne Maschette on (03) 9953 3041.

Please be advised that this study has been presented to and approved by the University Human Research Ethics Committee at Australian Catholic University. If at any time

parents have a query or complaint about the way that parent or child have been treated in this study, they may write care of the Office of Research.

Chair, University Human Research Ethics Committee
C/o Office of Research
Australian Catholic University
115 Victoria Parade
Fitzroy VIC 3065
Tel: (03) 9953 3157 Fax: (03) 9953 3305

Any complaint made will be treated in confidence, investigated fully and the participant informed of the outcome.

Should you agree that parents within your School community may be supplied with initial recruiting information for the study please phone:

Ms Vera Pelligrini, Administrative Officer
School of Human Movement (Victoria)
Australian Catholic University
03 9953 3041

Your School details will be recorded and I will contact you again regarding the timing of the project. Thank you for your co-operation with this important research.

Yours faithfully,

Dr Wayne Maschette, Principal investigator.

Motor Proficiency Project Information Pages

Preamble

This documentation is scientific in nature and has been extracted from the Exercise Science literature. It explains the rationale and procedures that are used in this project to investigate whether a child has movement problems. Where possible exercise science jargon is explained but certain aspects may not be clear on initial reading due to the complexity. The investigators are available to discuss these procedures and explain some of the technical jargon used. Much of the jargon actually relates to equipment and this can be explained in full by one of the research team.

Introduction

It is common knowledge that young children are involved in the process of developing and refining fundamental movement patterns from about 2 until about 8 years of age. It has been documented that to enhance their learning experiences, children should be exposed to a wide variety of skills in order to progress and develop their knowledge of the body and its potential for movement. These fundamental movement patterns are the building blocks for future involvement in many sports skills and their development should involve reaching acceptable levels of proficiency and efficient body mechanics in a wide variety of movement situations. The fundamental movement patterns involve only the basic elements and not complex patterns that are usually associated with sporting performance. For the purpose of research investigation, each fundamental movement is considered in isolation. For example, locomotion skills include running, jumping and leaping; while manipulative skills comprise of throwing, catching, kicking and trapping. All these patterns are mastered individually by the child first, but then are gradually combined and enhanced to produce complex skills. It has been reported that the basic elements of a fundamental movement should be the same for all children (Gallahue & Ozmun, 1995). This latter fact has given rise to the development of a set of aged based standards to which children can be compared. Unfortunately, these are northern hemisphere samples that do not adequately reflect the Australian cultural mix. It is our intention to develop Australian standards.

Two fundamental motor skills of interest to the research team are vertical jumping and the standing broad jump. The vertical jump is considered a fundamental motor skill for a variety of sports and recreational activities. It is also used as an estimation of the power a child's muscles can produce. Interestingly, Raynor (1999) has reported that for children who had poor motor proficiency (sometimes labelled clumsy) little is known of strength and power abilities; or the neuromuscular patterns associated with the force production as measured by vertical jump. We intend to link this power production with the measurement of the Australian standard of motor proficiency.

Similarly, the standing long jump has been used to discriminate between children of high and poor motor proficiency. During the performance of a standing long jump, Phillips et al. (1985) found in 3-7 year olds there were differences in take off characteristics which

included: changes in distance attained, the use of upper extremities, and a different take off angle. These differences can be used as discriminators between good and poor motor proficient children. It could therefore, be expected that children with a poor motor proficiency for their chronological age may display these same characteristics due to a delayed development.

Research Objectives:

The main objectives of the project include:

1. to collect normative motor proficiency data for children aged 6 to 12 years of age;
2. to determine if a relationship between power production during vertical jump and motor proficiency level exists for each age band
3. to identify any differences in the kinematic (speed) and kinetic (force) data which may be due to poor motor proficiency.

Research Design

Recruitment

Ethics approval has been obtained from ACU Human Research Ethics Committee prior to the commencement of recruiting. Permission from the state and catholic school education systems in the Melbourne has also been given (Education Victoria SOS001127 and Catholic Education Office GE99/0009). Upon approval by the School Principal, approach letters will be sent to parents/guardians, inviting children aged between 6-12 years to take part in the study. Upon obtaining sufficient numbers of replies, the school will be contacted and a suitable day(s), depending on numbers, will be arranged for testing. Accompanying the letter will be a very brief questionnaire related to developmental milestones, handedness/footedness and health status. This will be completed and returned by the parent/guardian.

Movement ABC, (Henderson and Sugden, 1992).

The Movement ABC will be used to measure coordination difficulties in the children. It has been validated as suitable for use in countries including the UK, Canada, USA (Henderson & Sugden, 1992), Sweden (Rösblad & Gard, 1998), Netherlands (Smits-Engelsman et al., 1998). To date no publications have addressed this issue of suitability in Australia.

The Movement ABC involves the checklist, this will be administered and involves the parent/guardian completing an inventory that is used to assess the child's daily functional living.

The final part of the testing procedure requires the child to perform a number of tasks from which their level of motor proficiency will be assessed. These tasks involve everyday skills, which are categorised into manual dexterity, ball skills and balance skills.

Location of testing

There are various options, ideally all testing will occur at the Gait Laboratories located at ACU, St Patrick's campus in Victoria Parade Fitzroy. This is very near to St Vincents' hospital. However, if this is not possible all equipment can be transported to the school. The school will then be requested to provide a suitable location, for example a gymnasium could be used. Throughout the testing process a trained administrator will accompany the child, this permits the building of rapport and facilitates optimal performance. Parents will not be encouraged to be present in the room with their child during testing. It is believed that the parent's presence may unintentionally put the child under adverse pressure to perform, which may affect the final outcome or just add to the risk of causing a distraction from the task. However, it must be stressed that throughout the process of testing the children will not be alone and strict supervision will be enforced.

Throughout the testing the children will be asked to wear clothing suitable for physical education, for example, t-shirt, gym shorts and trainers/shoes (rubber soled, no greater than 2.5cm in height). The clothes worn will be comfortable and allow freedom of movement.

Anthropometric assessment

In preparation for the vertical jump analysis component of the study, standard anthropometric data will be recorded using the guidelines in Ross and Marfell-Jones, (1991) these include: weight, height, leg length, foot length, shoulder breadth, and foot width.

Duration of testing

The duration of Movement ABC is suggested to be approximately 20-30 minutes for a well-coordinated child. Children with motor difficulties may take longer; the duration will then depend on fatigue and motivation factors. Occasionally the administrator may suspend the session allowing the child a break, returning to complete the tasks at a future date. An additional 15 minutes will be required to complete the screening process. The vertical jump test will take approximately 10 minutes to complete, excluding the warm-up.

Feedback

As a result appropriate feedback to parents will be given, regardless of the achievements. For those who exhibit 'normal' motor development, the parents will be informed that their child's development is in this area for their age. A breakdown of their child's performance in terms of each task will be given. For those who fall below the 15th percentile, the parents may be invited to discuss their child's motor development at an interview. At this time the parent would be given a summary of the problem areas that the child exhibits and recommendations for remedial programs or referral be made at a later date.

Vertical jump test

Reflective markers will be attached to body reference points such as the knee joint to assist in the analysis of the jumps. The nine body landmarks: centre of the head and the right shoulder, elbow, wrist, hip, knee, ankle, heel and 5th metatarsal. A video camera will be used to record the movement. A spotlight will illuminate the filming area and allow the reference markers to appear as bright spots in the camera field of view.

Prior to testing an instructional video will be presented to participants in order to standardise the information received by each child. Following will be a warm-up, which will include practices. The benefits of the warm-up will include putting the participants at ease, by allowing them to become familiar with the tasks and the surroundings. Further possible benefits for the subject include the suggested reduction in incidence and likelihood of musculoskeletal injuries, thus injury prevention. Warm-ups have also, been shown to facilitate the attainment of maximal efforts during jumping activities, due to physiological and psychological aspects.

All the data will be confidential and will not be published except as summaries according to age groups. School with children participating in the study will not be recognised in publications except as a general statement such as "School situated in the Northern region of Melbourne".



AUSTRALIAN CATHOLIC UNIVERSITY

Information Letter to Parents and Participants

Dear Parents,

We are conducting a study on motor skill development in children with reference to walking. The aim of the study is to help us to better understand the differences in children's development in this area so we can design better motor development programs. To do this we need children aged between 7-10 years to participate in the study that involves a number of simple tasks.

Tasks included in this study are throwing, catching, balancing, jumping, writing and walking. Some of the tasks are designed to represent everyday situations during walking, this includes avoidance of an object (negligible height) or stopping on a mat. During these tasks the children will be videotaped for later movement analysis. To ensure that the reference points have been correctly identified, reflective markers will be placed on the ankle and knee joints for example. All the tasks are safe, fun and incorporate a challenge, taking under two hours to complete in total (two sessions on separate occasions lasting no more than an hour each, including breaks).

Based on previous experience in testing with children we have found that subtle parental pressure can be placed upon the children to 'perform at their best' on various tasks. We stress that these tasks are not competitive but are aimed at establishing what motor skills have been mastered. It is therefore preferable, that the children be tested without parent's obviously visible to the children. Most of the time this will be accomplished by simply having parents in the background, but it may on rare occasions involve testing without parents being present in the testing room.

While all individual results will be confidential, the results from the study will help add to our understanding of how children's motor skill develop. At any time during the project you and your child are free to withdraw from the study.

At the end of the study, we will prepare a report for you outlining how your child performed on these tasks and your child's current level of motor development we will discuss this with you and your child.

If you would like your child to take part in this study, please fill in the attached consent form and return it to :

Dr Wayne Maschette
Australian Catholic University
School of Human Movement
115 Victoria Parade
Fitzroy, Vic 3065

Should you have any queries please contact Dr. Wayne Maschette on (03) 9953 3041

Please be advised that this study has been presented and approved by the University Human Research Ethics Committee at Australian Catholic University. In the event that you have a query or complaint about the way that you or your child have been treated during the study, you may write care of the nearest research branch of Office of Research

*Chair, University Human Research Ethics Committee
C/o Office of Research
Australian Catholic University
115 Victoria Parade
Fitzroy VIC 3065
Tel: 03 9953 3157
Fax: 03 9953 3305*

Any complaint made will be treated in confidence, investigated fully and the participant informed of the outcome.

If you agree that your child may participate in this project, please complete the details on both copies of the Informed Consent form and sign them, retain one copy for your records and return the other copy to the supervisor at the Australian Catholic University.

Thank you for your co-operation with this important research.

Yours faithfully,

Dr. Wayne Maschette, Supervisor



Australian Catholic University

Consent form : (Copy 1 – to be retained by Parent)

Child's Name

Date of birth

Gender

I, _____ of _____

Hereby consent to my child _____ participating in the research study on motor development to be taken by Dr. Wayne Maschette, Mr Noel Lythgo and Mr. Morgan Williams of Australian Catholic University.

I understand that

- (a) my child is free not to participate if he/she does not wish to do so and that he/she is free to withdraw at any time;
- (b) I am free to withdraw my consent at any time and withdraw any information supplied by my child;
- (c) Any videotaping of my child will only be used for assessment. It will not be shown to anyone not directly associated with the study without express consent;
- (d) The project is for the purpose of research and is not for treatment;
- (e) Any information my children or I supply will be confidential.

Signed _____ Date; _____
(Parent/Guardian)

Signed _____ Date; _____
(Parent/Guardian)

Australian Catholic University Limited A.C.N. 050 192 660
St. Patrick's Campus 115 Victoria Parade, Fitzroy, Victoria 3045, Australia
Mail: Locked bag 4115 Fitzroy MDC 3065, Australia
Telephone 61 3 9953 3041 Facsimile 61 3 9953 3095



Australian Catholic University

Consent form: (Copy 2 – to be retained by Supervisor)

Child's Name

Date of birth

Gender

I, _____ of _____

Hereby consent to my child _____ participating in the research study on motor development to be taken by Dr. Wayne Maschette, Mr Noel Lythgo and Mr. Morgan Williams of Australian Catholic University.

I understand that

- (a) my child is free not to participate if he/she does not wish to do so and that he/she is free to withdraw at any time;
- (b) I am free to withdraw my consent at any time and withdraw any information supplied by my child;
- (c) Any videotaping of my child will only be used for assessment. It will not be shown to anyone not directly associated with the study without express consent;
- (d) The project is for the purpose of research and is not for treatment;
- (e) Any information my children or I supply will be confidential.

Signed _____ Date; _____
(Parent/Guardian)

Signed _____ Date; _____
(Parent/Guardian)

Australian Catholic University Limited A.C.N. 050 192 660
St. Patrick's Campus 115 Victoria Parade, Fitzroy, Victoria 3045, Australia
Mail: Locked bag 4115 Fitzroy MDC 3065, Australia
Telephone 61 3 9953 3041 Facsimile 61 3 9953 3095

APPENDIX 4

Human Research Ethics Committee

Committee Approval Form

Principal Investigator/Supervisor: Dr Wayne Maschette Melbourne Campus

Co-Investigators: Mr Noel Lythgo Melbourne Campus

Student Researcher: Mr Morgan Williams Melbourne Campus

Ethics approval has been granted for the following project:

Kinematic and Kinetic comparisons for a maximal vertical jump with and without armswing.

for the period: 20.03.2001 to 31.03.2005

Human Research Ethics Committee (HREC) Register Number: V2000.01-38

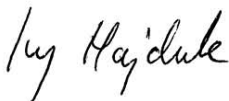
The following standard conditions as stipulated in the *National Statement on Ethical Conduct in Research Involving Humans* (1999) apply:

- (i) that Principal Investigators / Supervisors provide, on the form supplied by the Human Research Ethics Committee, annual reports on matters such as:
 - security of records
 - compliance with approved consent procedures and documentation
 - compliance with special conditions, and
- (ii) that researchers report to the HREC immediately any matter that might affect the ethical acceptability of the protocol, such as:
 - proposed changes to the protocol
 - unforeseen circumstances or events
 - adverse effects on participants

The HREC will conduct an audit each year of all projects deemed to be of more than minimum risk. There will also be random audits of a sample of projects considered to be of minimum risk on all campuses each year.

Within one month of the conclusion of the project, researchers are required to complete a *Final Report Form* and submit it to the local Research Services Officer.

If the project continues for more than one year, researchers are required to complete an *Annual Progress Report Form* and submit it to the local Research Services Officer within one month of the anniversary date of the ethics approval.



Signed: Date: ..20.03.01(Backdated).....
(Research Services Officer, Melbourne Campus)

APPENDIX 5

Spatial Reference System

The spatial reference system for the current study, defines Z as the movement in the vertical (upwards-downwards) direction, Y as movement in the anterior-posterior (forwards-backwards) direction and X as movement in the medial-lateral (sideways) direction (Figure A1). The direction of the Ground reaction forces (GRF) was described as vertical (V), horizontal (H) and medial-lateral (M-L).

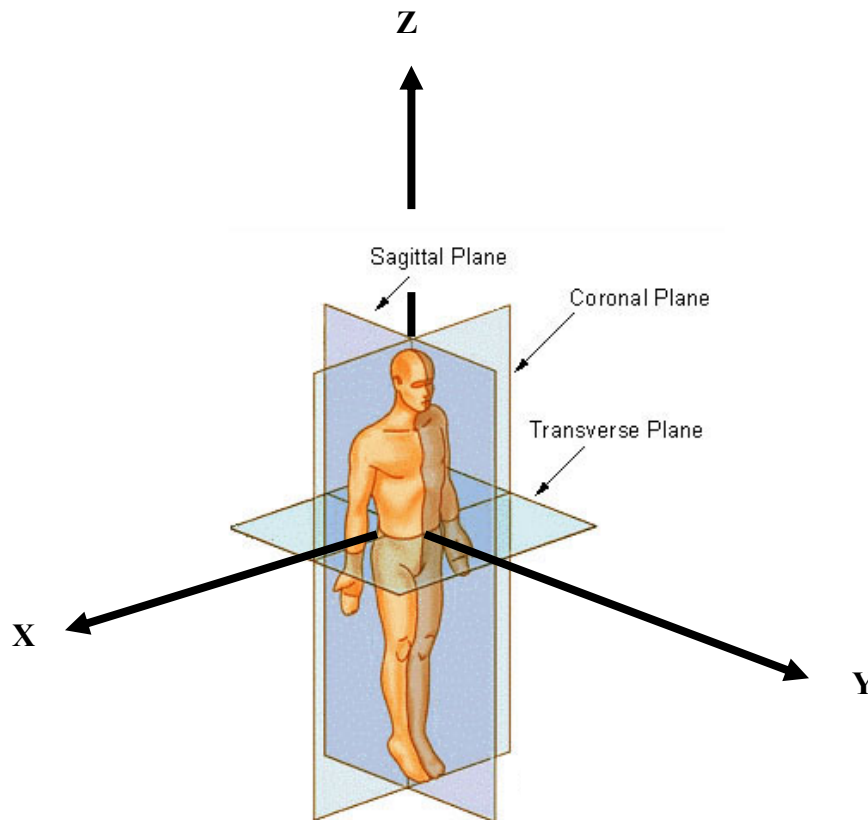


Figure A1: The spatial coordinate system used for the two-dimensional kinematic data collection and analysis (http://training.seer.cancer.gov/module_anatomy/unit1_3_terminology2_planes.html)

APPENDIX 6

Anatomical points of the body that were manually digitised.

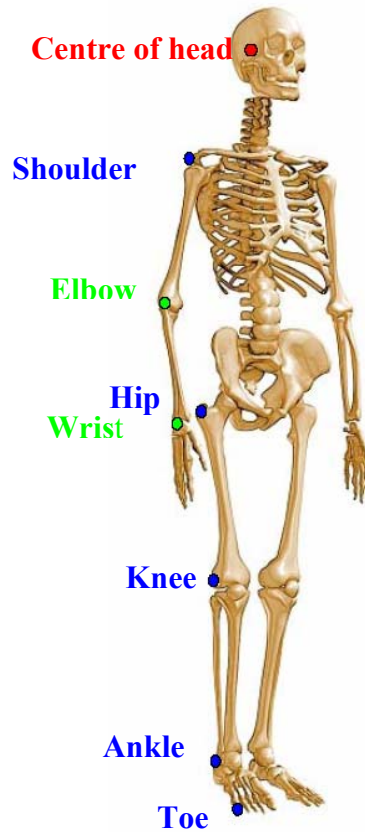


Figure A2: The eight points of the body that were manually digitised for each view of video footage during the two-dimensional analysis of vertical jumping.

The eight points digitised using Peak Motus software version 8.0 (Peak Technologies Inc.) included the centre of head (superior to the tragus of ear or at upper margin of zygomatic bone), shoulder (acromiale, superior and lateral border or the acromion process midway between the anterior and posterior borders of the deltoid when viewed from the side), elbow (proximal and lateral border of the head of the radius), wrist (ulnar styloid process), hip (greater trochanter), knee (lateral femoral condyle), ankle (lateral malleolus), and toe (fifth metatarsal), for the right hand side of the body only (Figure A2).

APPENDIX 7

The Vertical Jump: Some Known Technical Considerations

The duration of the whole jumping movement was determined from the instant of minimum force (peak negative VGRF) to the instant of take-off (Jensen et al., 1994). From practical experience and the data generated from the pilot study, the instant of minimum VGRF was the preferred starting point to define the jumping cycle. The previous use of a threshold value elsewhere in the literature (Feltner et al., 1999) of 4N did not produce consistent timing and was too sensitive to small movements (Typical Error = ± 0.096 s; CV = 14.9%). The duration from 4N below bodyweight (BW) to the instant of minimum VGRF appeared to be highly variable in the pilot study and stability of timing measures was more acceptable when minimum VGRF was used as the starting point of the jumping movement. Jump cycle time was therefore calculated as the time difference between the instant of minimum VGRF and take-off. The Figure A3 shows the VGRF curve sampled during a typical vertical jump attempt. The jump cycle is illustrated from the instant of minimum VGRF through to the instant of take-off. Jump cycle represented 100% of the Jump Cycle time, where 0% was equal to the instant of minimum VGRF and take-off occurred at 100% of jump cycle.

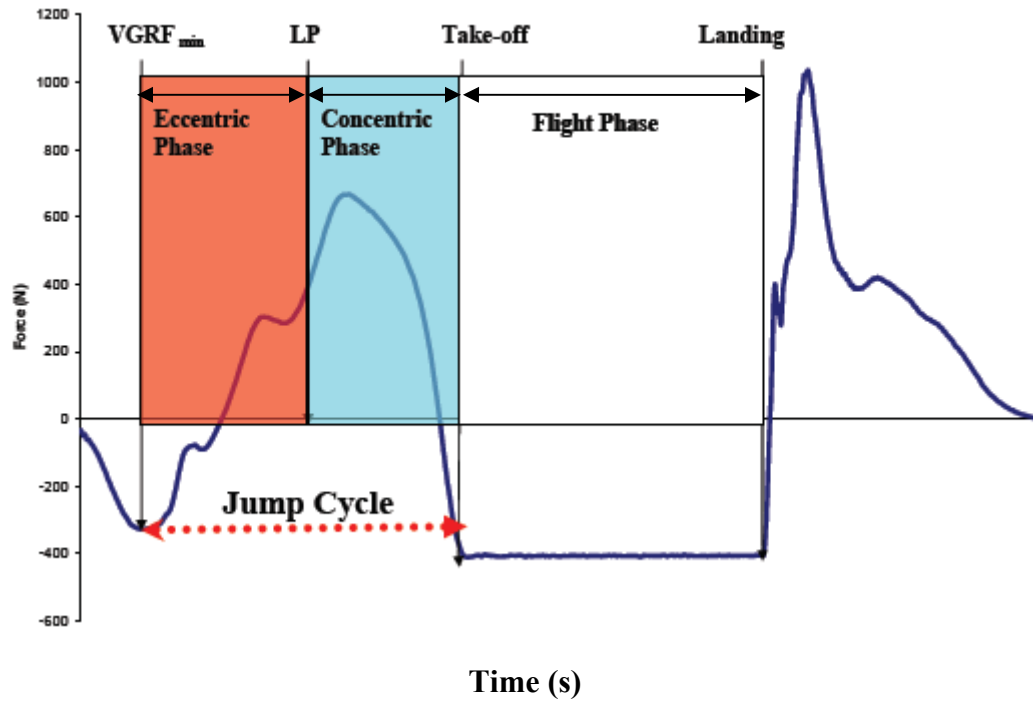
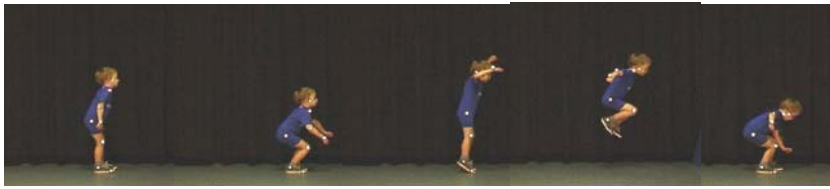


Figure A3: Time force curve of a jump cycle. The start of the movement was taken from the instant of minimum force ($VGRF_{min}$) and terminated at the instant of take-off. Flight phase occurred between the instant of take-off and the instant of contact with the forceplate (landing).

APPENDIX 8

Calibration of 2D Kinematics

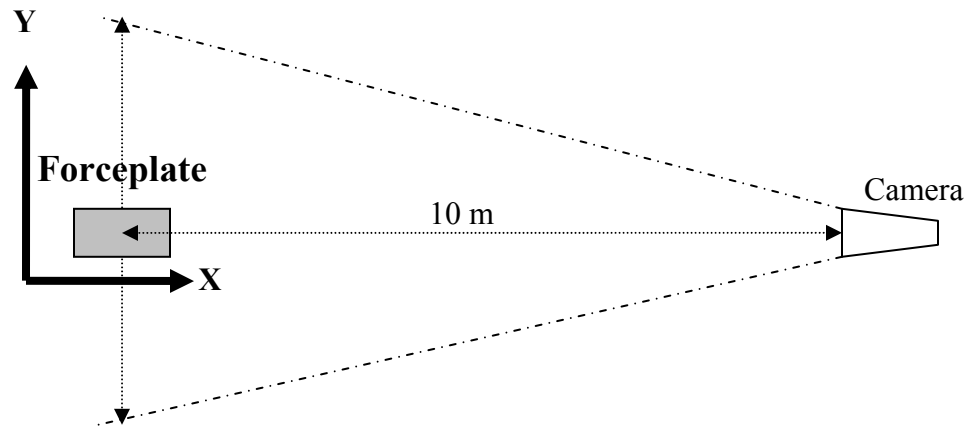


Figure A4: Camera set-up consistently used throughout data collection, the camera was set-up 10m perpendicular to the forceplate to capture the right-hand-side of the participant's body (sagittal plane) using the coordinate system where Y represents the anterior-posterior movements and X represents the medial-lateral movements (Z the vertical direction is not represented in the figure).

A single-camera (Panasonic Colour CCTV 50Hz genlock camera; model no. WV-CL830/G; Computar camera lens; model no. H6Z0812, 8-45 mm, 1:1.2) was used to collect the kinematic data (shown in Figure A4). All footage was collected on to video tape (NEC: E-195: VHS) using a Panasonic Super VHS Video Cassette Recorder (model no. AG4700). Previously, 60 Hz, the US equivalent of PAL video has been deemed sufficient to detect differences in timing of joint reversals and in timing of peak velocity differences between proximal and distal joints of each segment (Aragón-Vargas & Gross 1997b). The location of the camera and forceplate are shown in Figure A4. The camera (front of lens) was located 10 m from the centre of the forceplate, at a height (centre of the lens) of 1.60 m from the floor using a tripod (Manfrotto adjustable tripod).

The 10 m distance used for the camera location has been previously shown to provide accurate and reliable 2D kinematic data (Lythgo & Begg, 2004). The camera height was selected to represent the centre of the field of view allowing sufficient view to capture the whole jump movement. The camera was positioned on the right hand side of the participants with its optical axis oriented perpendicular to the sagittal plane of the participant, zoomed in to provide sufficient field of view to capture the movement (approximate FOV 3.5 m x 2.6m) minimising perspective error. The shutter speed was set at 1/1000 s to minimise blurring of markers during the jumping movement. A spotlight (ARLEC HL 18; 250 Watts; floodlight with adjustable stand) placed directly behind the camera was used to illuminate the filming area and allow the reference markers to appear as bright spots in the camera field of view.

Calibration of the 2D measurement plane was conducted in accordance to the guidelines in the Discovering Peak Motus: version 8 (Peak Technologies Inc, USA.). Horizontal calibration was performed by using reflective markers (3M reflective tape – high gain sheeting; make: 7610WS; dimensions 2 cm²) that were placed on a steel rod 1.50m in length (steel). The rod was placed at the centre of the forceplate, perpendicular to the camera. To ensure the camera was level the field of view was adjusted by zooming in and out. When the two markers displayed on the TV video monitor (38 cm Panasonic Colour TV Video Monitor; BT-M1420) disappeared simultaneously from the field of view in the horizontal and vertical planes, the camera was deemed to be level. Once level, the camera was zoomed out to provide the sufficient field of view to capture the whole jumping movement. The calibration frame was captured and recorded onto VHS videotape (NEC

E-195), the calibration frame contained two markers of a known horizontal distance of 1.50 m (from centre of one marker to the centre of the other marker) and was used in motion analysis. The equipment was secured and no adjustments were made to the focus or camera throughout the duration of the testing session to maintain a valid calibration frame.

Determination of Events

Take-off was the reference point (event) used to the kinetic (forceplate) and kinematic (video) data. Take-off was determined visually using the Peak Motus software, the field (split frame 50Hz) was advanced until the feet were free from the forceplate (Bobbert & van Ingen Schenau, 1988). The field that corresponded to take-off was then tagged as the “take-off” event in the software and used as a reference point.

The time before take-off of the individual peak joint and peak segmental angular velocities was established by counting the number of samples between the instant of interest and the previously marked instant of take-off. The number of samples was then multiplied by 0.02 s (the time of each sample: 50Hz).

The low point of SCOM was determined by the Kinetic data and represented the downward movement of the whole body. From the instant of low point derived from the kinetic data the number of samples from take-off for the corresponding kinematic data

was attained using the Equation A1. The duration from low point to take-off was divided by 0.02s to convert into the nearest whole number of samples.

$$\text{Number of samples from Take-off (nearest whole number)} = \frac{t_{lp} - t_{TO}}{0.02} \quad \text{Equation (A1)}$$

Where: tLP is the instant of low point and tTO is the instant of take-off

APPENDIX 9

Using the Forceplate in the Field, Estimated Noise during Data Collection

The VGRF data collected during flight phase were taken from the best attempts of ten, randomly selected participants from the current study and used to evaluate the noise (error) in forceplate signal. Flight phase was the time between take-off and landing where throughout this period no contact with the forceplate was made by the participant (displayed in Figure A5).

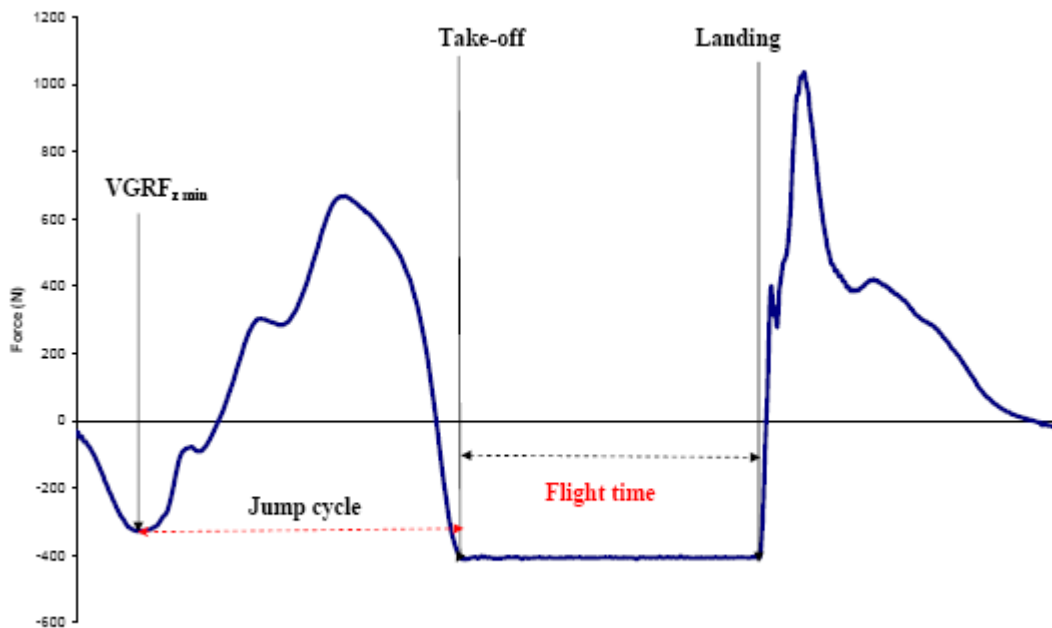


Figure A5: A sample of vertical ground reaction force (VGRF) data collected, following the automatic trigger which includes the instant of minimum VGRF ($VGRF_{min}$), take-off, landing and regaining quiet stance.

The VGRF data was adjusted to BW, so during quiet stance the measurement recorded was zero N for every sample. During flight phase, only gravity, which is constant, was recorded (700Hz). Therefore, flight phase VGRF data was equal to $-BW$, as seen in the

Figure A5. It was assumed that in the absence of all sources of noise (error) the VGRF data throughout the flight phase would remain constant (-BW). Total noise would be represented by the standard deviation (variability) in the collected VGRF data during flight. As the standard deviation represents the variability of a data set, the group (n = 10) mean of the standard deviation of the VGRF data recorded during the flight phase was used to represent an estimation of total noise during kinetic data collection. The statistical methods to attain typical error are shown in Equation A1 and described in detail by Hopkins (2000).

The Coefficient of Variation (CV) represents a dimensionless measure to describe the expected error (Equation A2). The advantage of using CV compared to an absolute measure is that the error can be related to the magnitude of the participant's BW (heteroscedasticity). From Table A3 it can be seen that the estimated total noise in the forceplate signal was $\pm 1.5\text{N}$. The accuracy expressed as a coefficient of variation for each VGRF sample collected was within 0.6% of -BW.

$$CV\% = \left(\frac{SD}{Mean} \right) \times 100 \quad \text{.....Equation (A2)}$$

Table A3: To show the mean maximum, minimum, average, standard deviation (SD) and coefficient of variation (CV) for the vertical ground reaction force (VGRF) data collected during the flight phase.

<i>Mean VGRF during flight phase</i>	
Maximum (N)	-247.9
Minimum (N)	-259.1
Mean (N)	-253.2
SD (N)	1.5
CV (%)	0.6

The precision of measurement was further assessed by using the mean BW data collected during quiet standing and the data during flight phase (Table A4). Bodyweight (BW), measured independently from the jumping trials (mean BW = 253.1 ± 73.5 N) was compared to the mean VGRF data collected during flight (mean negative BW = -253.2 ± 74.9 N) for the ten randomly selected trials. It was assumed that the measure of BW during quiet stance and -BW during flight phase would not significantly differ if the data collection was accurate. Typical Error (Equation A3) was found to be within ± 1.5 N (CV = 0.6 %) when BW measured during quiet stance and mean absolute BW measured during the flight phase (Table A4). A dependent t-test between the mean BW measured independently and mean negative BW during flight (absolute values) was used to establish that no systematic error (bias) was observed. The mean difference between BW and mean - BW measures was -0.1 N which was not significant (t = - 0.152; df = 9; p = 0.883) as shown in Table A5.

$$TE = \left(\frac{SD_{Diff}}{\sqrt{n}} \right) \quad \text{..... Equation (A3)}$$

Where: TE is the typical error, SD_{diff} is the standard deviation of the differences between BW and the BW measured during flight; n is the number of trials.

Table A 4: To show the mean bodyweight (BW) during body mass assessment and flight phase, the mean difference between measures, and the mean BW.

	BW (N)	Negative BW during Flight phase (N)	Difference (N)	mean BW (N)
Mean	253.1	-253.2	-0.1	253.1
SD	73.5	74.9	2.1	70.4

The estimated total noise from the error analysis supported the efforts made to minimise total noise (error). Moving the forceplate from the laboratory to the classroom did not adversely affect the quality and precision of measurement with measures made within acceptable levels in absolute (TE) and relative (CV) terms. Using the VGRF data collected that was to be analysed, was justified as it reflects the specific data used throughout the testing rather than a separate study.

Table A5: T-test output for the mean BW measured and BW recorded during the flight phase.

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	BWT - BWTflight	-.10055	2.09851	.66361	-1.60174	1.40064	-.152	9	.883

APPENDIX 10

Determination of the Instant of Take-off from Kinetic Data Collected in the Field

Take-off was established in the main study by using a threshold of 3 N, this value was established and rationalised by the TE analysis discussed in the previous section from the randomly selected trials ($TE = 1.5 \text{ N}$: for 95% confidence $\times 1.96$). Previously, a threshold value to establish the initial movement was reported to be between 0.7-2.0 N for young heavier adults under laboratory (Street et al., 2001). The previously lower threshold for identifying take-off was used by measuring the peak value during the standing period. For the present data, the use of an automatic trigger and independent measurement of BW did not permit this type of error analysis to be made, although during the independent weighing of individuals, mean BW for a 3 second period was recorded in the software, the data sample collected was not available. A larger threshold for the present study was set when compared to that based on data in a laboratory setting (Street et al., 2001). Testing outside the laboratory and being based at the school was important and provided ecological validity to the study. The ecological validity was a priority because of the effect an unnatural environment such as a laboratory can have on children (Robertson, 1987).

APPENDIX 11

General Kinetic Analysis

The kinetic data, which included Ground Reaction Force (GRF) in all three directions (V, H and M-L) was saved to the hard disc of the computer. On completion of the study, all data was exported into a custom written Microsoft® Excel® spread sheet. The VGRF data were normalised for BW measured independently. Therefore if quiet standing had occurred during the data collection every participant would have a force equal to 0 (zero) N. Using the instantaneous VGRF data, acceleration, velocity and displacement of the centre of mass (COM) were determined as shown in Figure A6. The COM represented the “point at which the mass is evenly distributed” (Hamill & Knutzen, 2003, p.385) it is the sum of all the moments of the separate segment forces (Hay, 1993). Therefore, it represents the orientation of the body’s segments and therefore acceleration, velocity and displacement of the whole body.

$$a(t) = \frac{F(t)}{m}$$

$$v(t) = \sum_{i=t_i}^{t_f} (a(i + \delta t) + a(i)) \cdot \frac{\delta t}{2}$$

$$s(t) = \sum_{i=t_i}^{t_f} (v(i + \delta t) + v(i)) \cdot \frac{\delta t}{2}$$

$$P(t) = F(t) \cdot v(t)$$

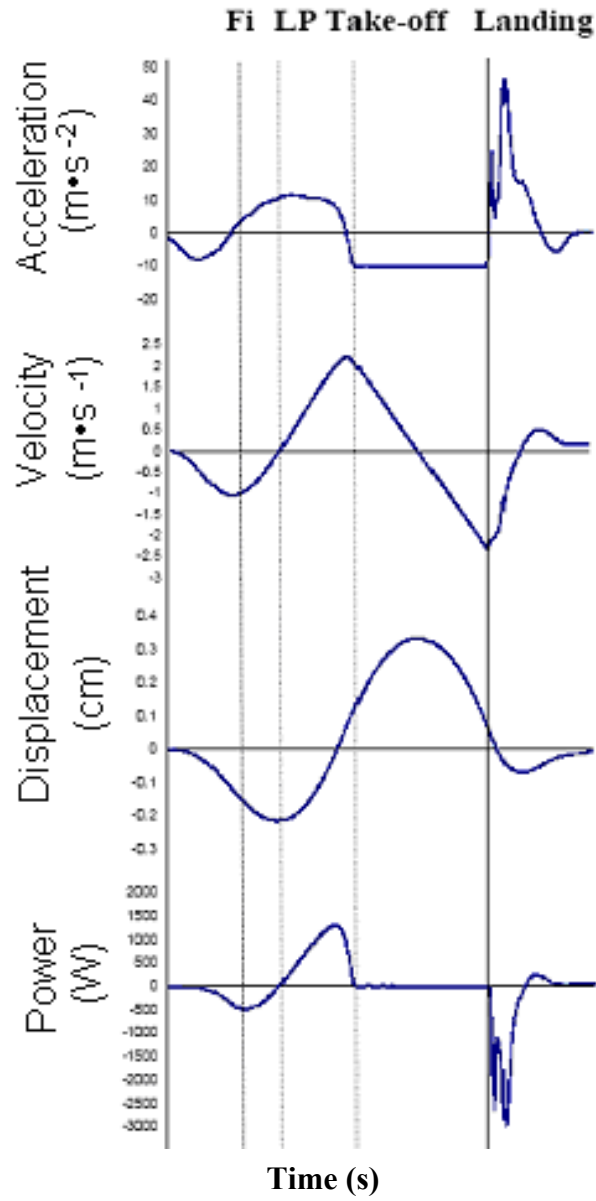


Figure A6: The calculation of acceleration from force (top). The discrete integration of the acceleration data to calculate, velocity (second from top), displacement of the centre of mass (second from bottom) and the product of force and velocity, power (bottom) (where: a = acceleration, F = VGRF, m = mass, P = power, δt = sample rate, i = initial time).

Acceleration of the Centre of Mass

For every participant all files containing the forceplate data for each jump attempt were analysed using the data exported in to Microsoft® Excel ®. The instantaneous vertical ground reaction force (F) data was divided by mass (m) to calculate instantaneous acceleration (a) as follows:

$$a(t) = \frac{F(t)}{m} \quad \text{.....Equation (A4)}$$

Where: a is acceleration, F is the vertical ground reaction force and m is the mass of the participant.

Vertical Velocity of the Centre of Mass

From acceleration data (Equation A4), since calculations were done in the discrete domain the trapezoidal rule (Burden & Faires, 2004) was used to calculate velocity vertical velocity of the centre of mass (v) (Equation A5).

$$v(t) = \sum_{i=t_i}^{t_f} (a(i + \delta t) + a(i)) \cdot \frac{\delta t}{2} \quad \text{.....Equation (A5)}$$

Where: i is the initial and t_f is the time of the final instants. δt is the sample frequency (1/700 s).

Vertical Displacement of the Centre of Mass

The second discrete integration gives the vertical position of the COM (s). Since calculations were done in the discrete domain the trapezoidal rule was used to calculate displacement (Equation A6)

$$s(t) = \sum_{i=t_i}^{t_f} (v(i + \delta t) + v(i)) \cdot \frac{\delta t}{2} \quad \dots\dots\dots \text{Equation (A6)}$$

Power Output

Power output was the product of force and velocity (Equation A7)

$$P(t) = F(t) \cdot v(t) \quad \dots\dots\dots \text{Equation (A7)}$$

Therefore max power is calculated by

$$P_{\max} = \max [P(t)] \quad \dots\dots\dots \text{Equation (A8)}$$

The integration method has been recommended in preference to the use of the COM derived from inverse dynamics in two-dimensions (Kiebele, 1998). The recommendations for using forceplate data came from Kiebele (1988) who compared the estimated COM position established from high speed kinematic data (200Hz) and mass-inertial characteristics of human body segments to the integration method of kinetic data. In summary, Kiebele (1988) suggested that the use of kinematic and centre of gravity models can cause errors. Furthermore, as a consequence of growth, the difficulties and

errors associated with estimations from using the mass-inertial characteristics of human segments to calculate the centre of mass for specifically children are further increased and discussed elsewhere in detail (Jensen, 1981a; 1981b, 1986, 1987, 1988; 1989).

Maximal Jump Height

Jump height, was the vertical displacement of the centre of mass (SCOM) from starting position established using BW from quiet standing to peak SCOM (Bobbert et al., 1996). Jump height included the COM position at take-off in addition to the peak SCOM during the flight phase as shown in Figure A7.

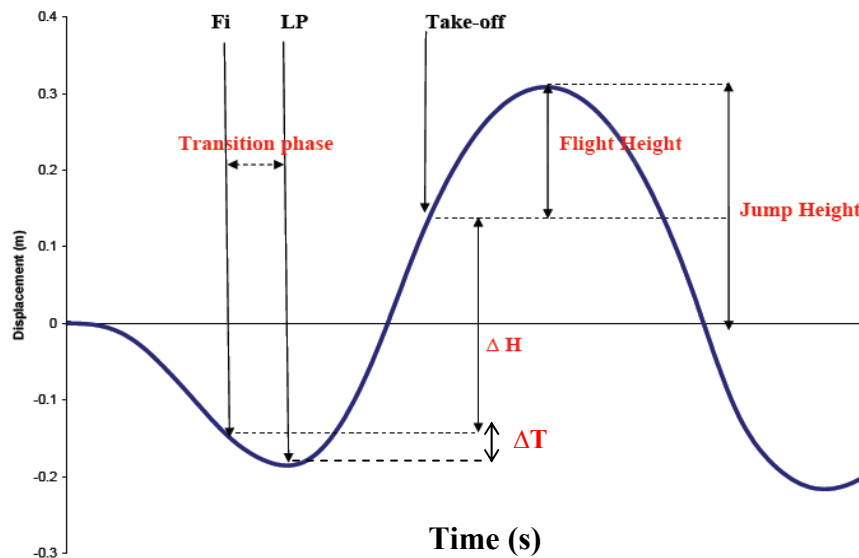


Figure A7: Displacement of the centre of mass (SCOM) throughout the jump movement.

Position of Centre of Mass at Take-off

The centre of mass (COM) position at take-off was a particular interest for the present study that was generated from the developmental literature where qualitatively children who display an immature movement pattern fail to fully extend the whole body at take-off (Gallahue & Ozman, 2002; Hoare & Larkin, 2001). The COM position at take-off was therefore used to give an indication of the extent of the whole body extension from initial position to the instant of take-off. For the forceplate data, the instant of take-off was defined as the instant the body departed from the forceplate (see Figure A5). Take-off, was determined when the VGRF was equal to or within 3 N of negative BW (-BW) described earlier in appendix A3. Once established, the instant of take-off was also used as a point of reference for other timing variables to be compared to and is used consistently throughout the literature (e.g., Bosco et al., 1982).

Flight Height

The difference between jump height and SCOM at take-off was termed ‘flight height’ (see Figure A7) and represents the SCOM once the feet have departed from the surface. Flight height is similar to calculations made from VCOM at take-off, flight time and from jump impulse, because the position at take-off is not considered. However, differences exist and therefore flight height cannot be compared directly to other studies that use VCOM at take-off, flight time and jump impulse to calculate flight height (Aragón-Vargos, 2000).

With an interest in the contribution of the COM position at take-off to jump height, the contribution of COM at take-off to jump height was reported as a percentage using the following Equation:

$$\text{Percentage contribution} = \left(\frac{SCOM_{\text{Take-off}}}{\text{JumpHeight}} \right) \times 100 \quad \text{.....Equation (A9)}$$

Where $SCOM_{\text{Take-off}}$ is the COM position at take-off.

Centre of Mass Displacement at the Low Point

The countermovement is important to vertical jumping by permitting force to be actively developed as the muscles are stretched, increasing the depth of the countermovement can permit greater force to be actively produced augmenting jump performance (Bobbert et al., 1996). From the instantaneous SCOM, the low point of the countermovement was identified as the lowest value (Figure A7) this was considered to represent the amplitude of the countermovement from the initial position determined from the BW. With the instant of low point established the force at low point was recorded (Figure A7). In addition, the time interval from the low point to take-off was used to define the initiation of the concentric phase, where the body moved upwards until take-off (Figure A3). The concentric phase was also reported relative to the whole jumping movement as a percentage.

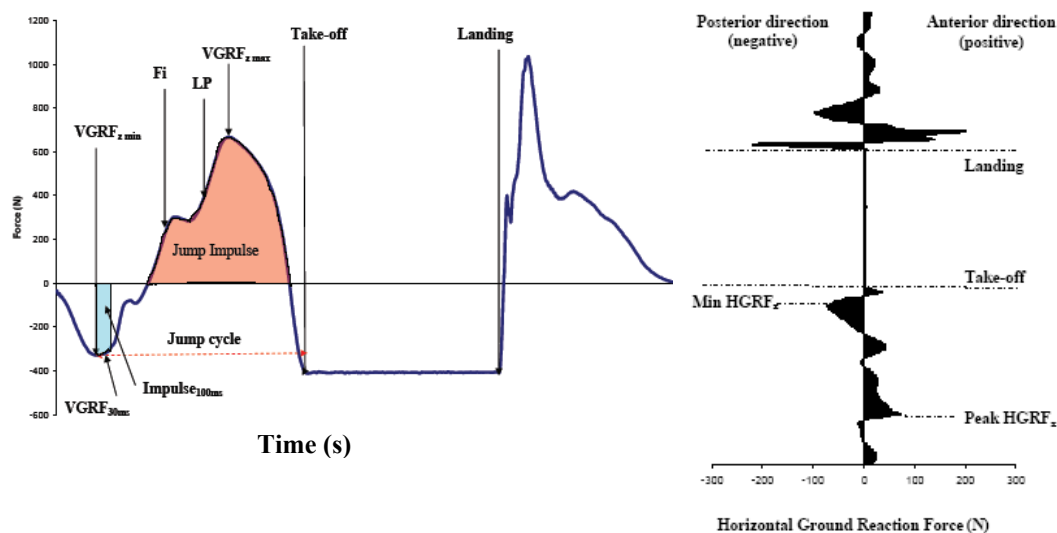


Figure A8: A sample of the vertical ground reaction force (VGRF) and horizontal ground reaction force (HGRF) during a single maximal vertical jump attempt.

Force, Jump Impulse and Power Output during Jumping

Jumping is an explosive movement, requiring the body to actively develop force from the raw forceplate data exported, timing and magnitudes of GRF in the vertical (Z) and horizontal (Y) directions (Minimum VGRF, Peak VGRF; Minimum HGRF, Peak HGRF) throughout the jumping movement were collected (Figure A8). Minimum VGRF referred to the peak magnitude of the force variable in the negative direction (Figure A8). Whereas, the peak VGRF represented the greatest actively developed force produced in the vertical direction during the jumping movement.

The nature of the jumping task required the body to be displaced vertically maximally, therefore, horizontal displacement would be minimised. The minimum HGRF represented the maximal force in the posterior direction whilst the peak positive HGRF represented the peak anterior force (Figure A8). In addition, the magnitude of horizontal displacement of the toe marker, from take-off to landing was used to quantify the departure from the initial position.

Using the impulse-momentum relationship, the explosive movement of jumping is determined by the force produced over a period of time. Vertical Jump Impulse (Jump impulse) was calculated using the Equation A10 (Dowling & Vamos, 1993). Jump impulse was determined by the area of force above BW during the concentric phase (shaded area in Figure A8).

$$\text{Jump impulse} = \sum_{i=t_i}^{t_f} (F(i + \delta t) + F(i)) \cdot \frac{\delta t}{2} \quad \dots\dots\dots \text{Equation (A10)}$$

Where: t_f and t_i is the time interval when VGRF (F) was above bodyweight (as force was normalized for bodyweight = zero VGRF).

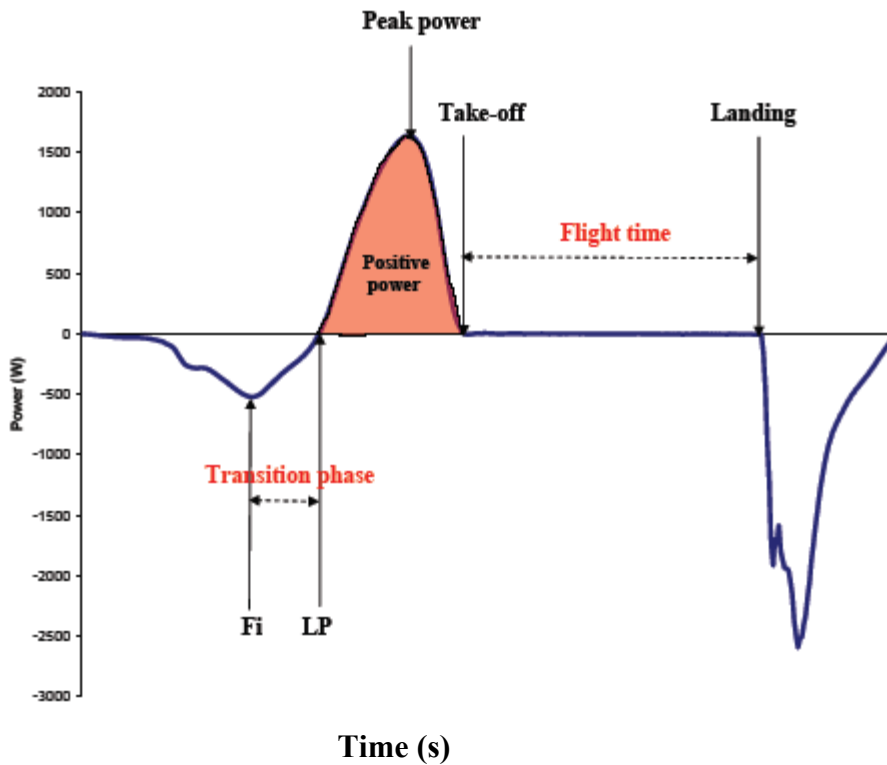


Figure A9: Determination of the power variables.

The combined relationship of force production and velocity of movement was identified to be an important quality that may distinguish between children identified with DCD and those typically developing (Raynor, 2001). Therefore to compliment the force variables calculated, the product of the instantaneous VGRF and instantaneous VCOM was used to calculate instantaneous power (Equation A7). The measurements used to evaluate power output were peak positive power output and average positive power (Figure A9).

From the instantaneous power, the magnitude and instant of peak positive power was recorded (Figure A9). In addition, the average positive power was calculated by using the integral of positive mechanical power (Equation A11). The average power was calculated

from the area of the curve once power had become positive and is identified as the red shaded area in the Figure A9 (Bosco, 1992; Harman et al., 1990). The instant following peak negative power was noted and represented the instant of Instantaneous Force (Fi) (Bosco, 1992). Peak positive mechanical power and average mechanical power were both reported relative to body mass ($\text{W}\cdot\text{kg}^{-1}$) in accordance with the recommendations for samples of children (Bar-Or, 1996; Docherty, 1996).

$$\text{Average power} = \frac{\sum_{t_i}^{t_f} P}{n} \quad \dots\dots\dots \text{Equation (A11)}$$

Where: t_i to t_f is the time interval from when power (P) was positive and n was the number of samples.

APPENDIX 12

Kinetic Analysis (coordination) of the Transition Phase

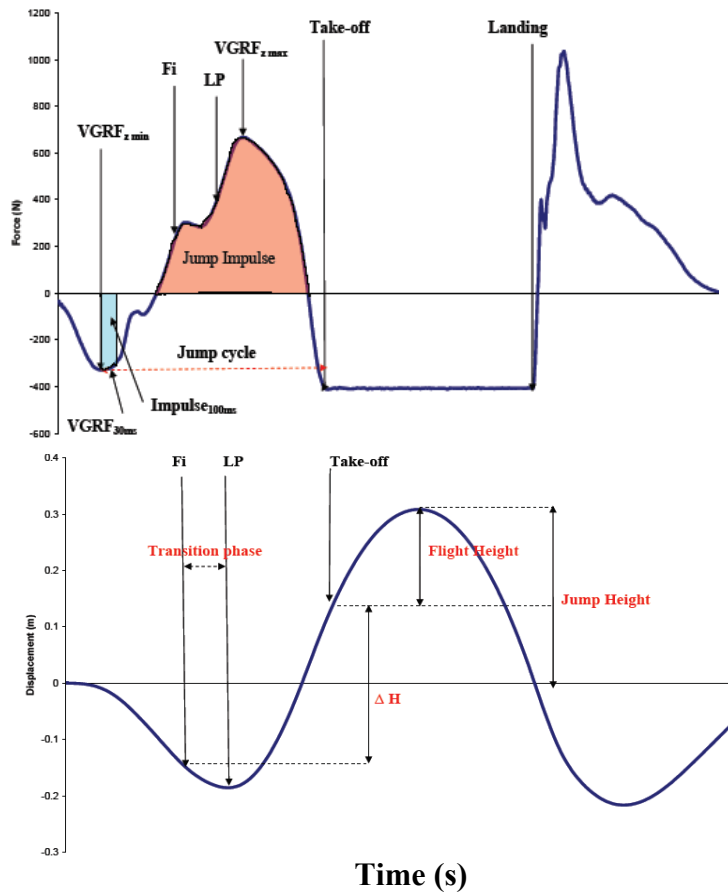


Figure A10: Eccentric Loading, Eccentric Rate of Force Development, Transition and Leg Stiffness.

From the observations of Raynor (2001), children identified with DCD had particular difficulties with transitions at higher task velocities during knee joint extension to flexion transitions. For jumping, the transition occurs during the countermovement in preparation for take-off. The coordinated effort of the lower limbs involves a number of joints, therefore the demands were assumed to be greater and more complex than those imposed by Raynor (2001). Assuming that the single joint task assessed by Raynor (2001) was a

valid assessment, the higher task demands and increased complexity of the countermovement, would therefore display differences between DCD and TD groups.

The low point resembles the instant where the change from a downward (eccentric) to upward (concentric) movement occurred. Before the low point a transition phase is initiated at the instant of instantaneous force (F_i). The F_i is represented by the VGRF (with the BW subtracted), at the instant, when the mechanical power first moves in a positive direction (Bosco, 1992) or in other words the first sample following the instant of peak negative power. Figure A10 shows instantaneous power (bottom right curve) with F_i identified by a vertical line. The instant of F_i is then taken to the SCOM curve (above the power curve) to determine the displacement at that instant and also to the force curve (top right hand side curve) to determine the VGRF (-BW).

It has been proposed that at the instant of F_i the muscles are activated and act quasi-isometrically holding the muscle at its optimal length, whilst the tendon is stretched, permitting energy to be stored (e.g., Kubo et al., 1999). The duration between the instant of F_i and low point gives the time of the transition from the eccentric to concentric actions which was referred to as the transition phase (Bosco, 1992). In the literature this has also been referred to as the stretching time (Kiebele, 1998).

$$\text{Transition phase duration} = F_i(t) - LP(t) \quad \dots\dots\dots \text{Equation (A12)}$$

Where: $F_i(t)$ is the time of instantaneous force and $LP(t)$ is the moment of low point during the countermovement

The vertical displacement of the centre of mass that occurs during the transition phase (ΔT) may provide useful information to the properties and abilities of the Muscle Tendon Complex (MTC). The ΔT was calculated which has also been referred to as the stretching distance elsewhere in the literature (Kiebele, 1998). The ΔT was calculated from instantaneous SCOM as the difference between the SCOM at the instant of F_i and SCOM at low point (Equation A13).

$$\Delta T = (F_{iCOM} - LP_{COM}) \quad \dots\dots\dots \text{Equation (A13)}$$

Where ΔT is the centre of mass vertical displacement during the transition phase; F_{iCOM} is the displacement at the instant of instantaneous force and LP_{COM} is the displacement at the instant of low point

The smooth transition from flexion to joint extension requires precise inter-muscular coordination. Leg stiffness (K_{leg}) was calculated and used as an indirect measure of lower extremity (leg) muscle co-activation during the transition from flexion to extension.

Calculated by using the Equation A14 (Bosco, 1992) it was hypothesized that an appropriate level of inter-muscular coordination would be required resulting in a particular K_{leg} , dependent upon the physical characteristics of the individual. However, poor control may be identified by excessive K_{leg} caused by a high-level of muscle co-activation or lower than expected level of K_{leg} , would be caused by insufficient co-activation that may cause collapsing of the lower limb.

Previously for K_{leg} the hip marker was used to assess the SCOM in children (Wang et al., 2003), however, errors due to synchronization of video (50 Hz) and that the hip marker displacement is unaffected by the relatively large mass of the trunk made the SCOM derived from the force data more appropriate. Furthermore, the method described for running and hopping by Farley and Gonzalez (1996) where VGRF at low point has been used was also inappropriate. For this calculation of K_{leg} , it was assumed that maximal VGRF coincides with the instant of low point, which for the Counter Movement Jump with arm-swing is not the case. From the pilot study the differences in timing can be seen where mean time for the instant of low point occurred at 0.457 ± 0.092 s and the instant of mean peak VGRF followed at 0.587 ± 0.114 s into the jumping movement. Therefore, K_{leg} was calculated using Bosco (1992) which was developed specifically for jumping.

$$K_{\text{leg}} = \frac{(F_i + BW)}{\Delta H} \quad \dots\dots\dots \text{Equation (A14)}$$

Where ΔH = is the difference between the displacement at take-off ($SCOM_{TO}$) and the displacement at the moment of instantaneous force ($SCOM_{Fi}$); F_i is the VGRF at instantaneous force and BW is the bodyweight of the participant.

To represent the eccentric rate of force development or loading during the countermovement the force produced at 30 ms (starting strength) impulse over the first 100 ms ($Impulse_{100ms}$) following the minimum VGRF (Wilson et al., 1995) were selected. A difficulty suggested for poor performance by children is the lack of strength to control the downward phase (Jensen et al., 1994). The initial eccentric loading is the ability to develop force rapidly following peak negative VGRF and was quantified as the force produced at 30 ms (starting strength) and impulse over the first 100 ms ($Impulse_{100ms}$) (Wilson et al., 1995). Both measures gave an indication of the force developed and experienced during the initial moments of transition phase. In addition, the Peak negative VCOM ($VCOM_{min}$) was used to indicate the peak velocity of the countermovement (Kibele, 1998).

$$\text{Impulse (N}\cdot\text{s)} = \sum_{t_i=i}^{t_{100ms}} (F(i + \delta t) - F(i)) \cdot \frac{\delta t}{2} \quad \dots\dots\dots \text{Equation (A15)}$$

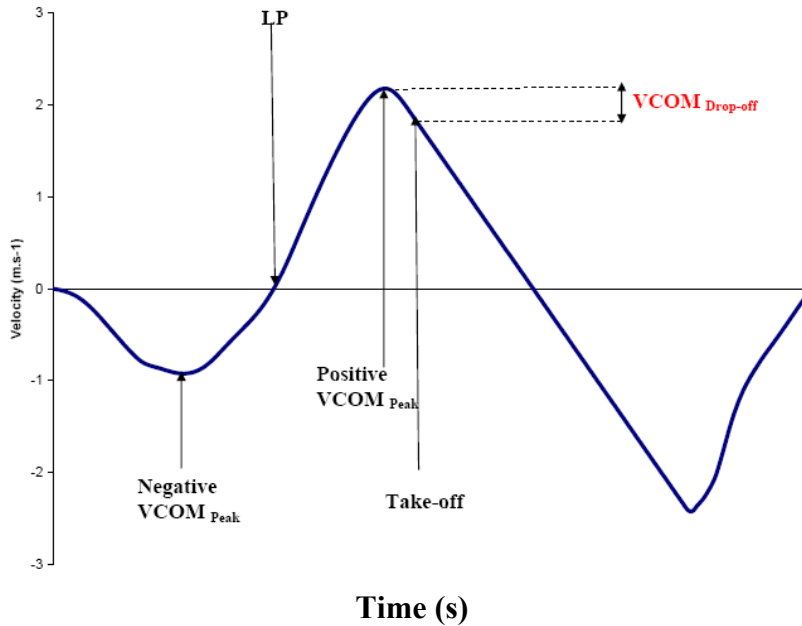


Figure A11: Vertical velocity of the centre of mass (VCOM) variables.

Vertical Velocity of the Centre of Mass

The Vertical Velocity of the Centre of Mass (VCOM) at take-off is important to jumping and represents the whole contribution of the body. Using the instantaneous VCOM, $VCOM_{take-off}$ was established (Figure A11) from the already determined event of take-off (Figure A11). In addition, the instances and magnitudes of minimum and peak VCOM were identified and recorded (Figure A11).

The peak VCOM determined from the instantaneous VCOM data was used to indicate the quickness of the jumping movement. To maximise jump height, reaching peak VCOM as close to the instant of take-off requires an efficient and effective coordination

of the body's segments (Bobbert & van Soest, 2001). The time elapsed between peak VCOM and take-off has previously been used to reflect neuromuscular coordination of jumping in children aged between five to eight year olds (Falk et al., 1997). Furthermore, loss in VCOM from the instant of peak VCOM and take-off was used to show the efficiency of the jumping movement. The difference between peak VCOM and $VCOM_{take-off}$ was called $VCOM_{drop-off}$ (Figure A11). The $VCOM_{drop-off}$ was expressed as a percentage of peak VCOM (Equation A16) to account for the differences in peak VCOM. It was assumed that the greater the loss (drop-off) in VCOM the less efficient the jumping movement.

$$VCOM_{drop-off} = VCOM_{peak} - VCOM_{take-off} \dots\dots\dots \text{Equation (A16)}$$

$$\text{Percentage drop-off in velocity (\%)} = \left(\frac{VCOM_{Drop-off}}{VCOM_{peak}} \right) \times 100 \dots\dots\dots \text{Equation (A17)}$$

APPENDIX 13

Normalising for Body Size: Displacement of Centre of Mass

Physical size, which is represented by stature and mass has been shown to influence jumping performance in children (Bosco & Gutstafson, 1983). Although participants were matched for size and age, jump height data were normalised for stature.

Normalising using stature has been a suggested approach used to scale jump height performance and other SCOM variables (Aragón-Vargas & Gross, 1997a; Butterfield et al., 2004). However, from the present findings the correlations were low between stature and all SCOM variables (Figures A12 and A13), therefore, normalised SCOM for stature was not used in the study. Correlations with stature were $r_{xy} = 0.206$, $r_{xy}^2 = 0.042$; $p = 0.022$ for jump height; $r_{xy} = 0.337$; $r_{xy}^2 = 0.114$, $p < 0.001$ for SCOM at low point, $r_{xy} = 0.034$, $r_{xy}^2 = 0.001$, $p = 0.711$ for SCOM at take-off and $r_{xy} = 0.337$; $r_{xy}^2 = 0.118$; $p < 0.001$ for flight height.

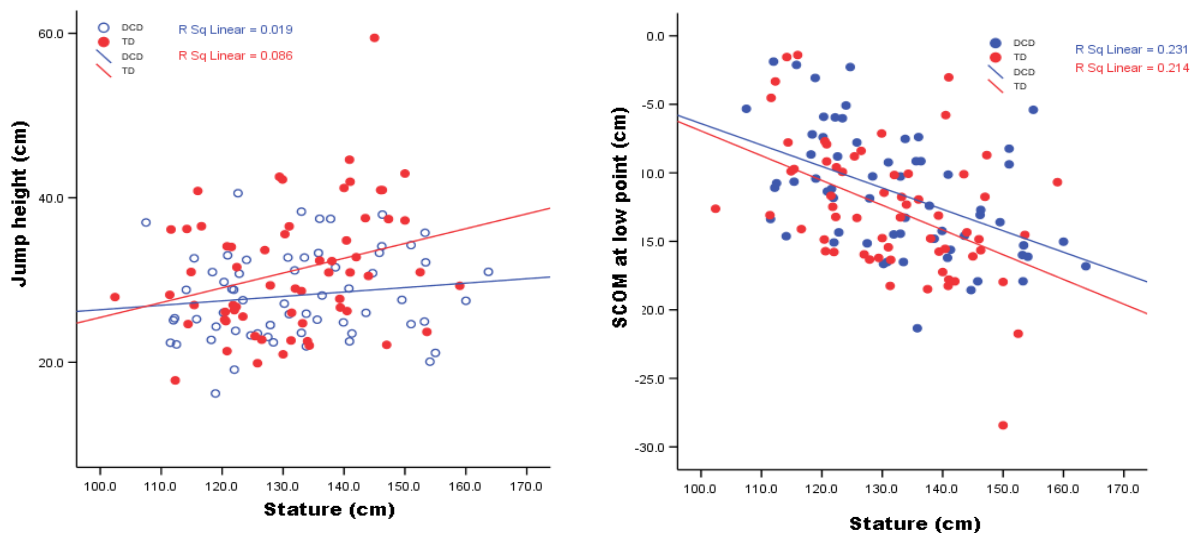


Figure A12: Relationship between stature and jump height (left panel) and, stature and centre of mass displacement (SCOM) at low point (right panel).

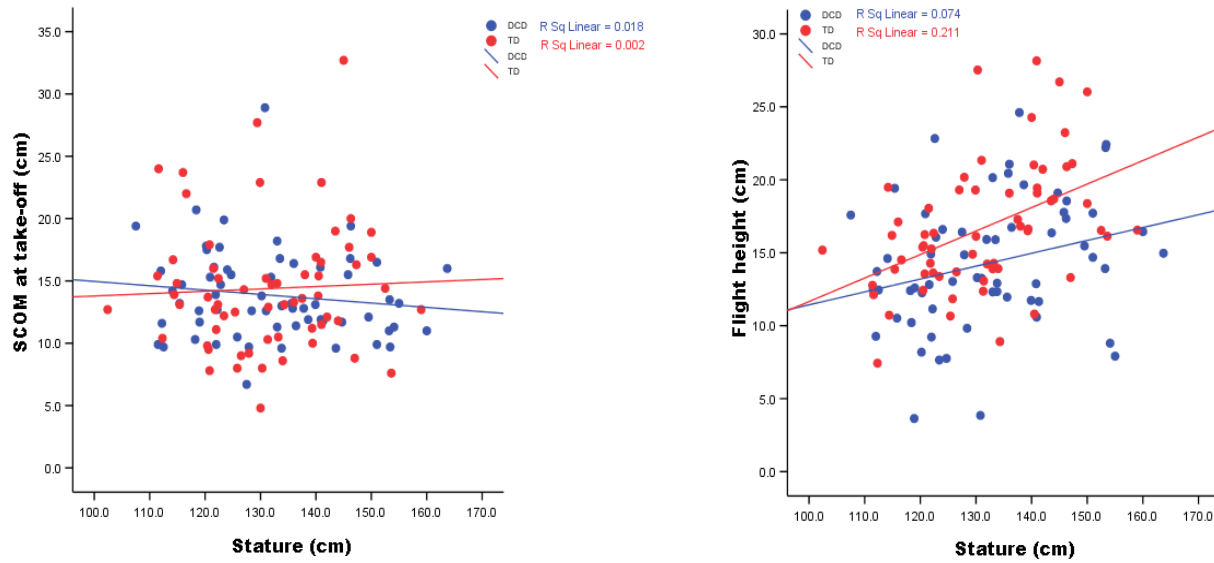


Figure A13: Relationship between stature and centre of mass displacement (SCOM) at take-off (left panel) and, stature and flight height (right panel).

Normalising for Body Size: Force, Jump Impulse and Power Output

All GRF and impulse variables were analysed with and without normalising to BW due to the inherent relationship between force and mass (Bosco & Gustafson, 1983). In addition the power output variables were reported with and without normalising to body mass (kg) following convention and previously reported data of power output by children (e.g., Falk et al., 1997). The reporting of normalised force and power variables only was justified in this study due to the clear relationships found with body weight or mass. All correlations (all significant to $p < 0.001$) are presented in the Table A6 with the relationships for peak power, average power, peak VGRF and jump impulse graphically shown in Figures A14 and A15.

Table A6: Relationships between Force and power variables with body size (Mass or Bodyweight) all were significant $p < 0.001$.

		mass	bwt	Jump Impulse (N)	min Fz (N)	maxFz (N)	min Fx (N)	maxFx (N)	Peak Power (W)	Average power (W)
Mass	Pearson Correlation	1.000	1.000	0.952	-0.737	0.741	-0.595	0.503	0.902	0.868
Bwt	Pearson Correlation	1.000	1.000	0.952	-0.737	0.741	-0.595	0.503	0.902	0.868
Jump Impulse (N)	Pearson Correlation	0.952	0.952	1.000	-0.807	0.747	-0.656	0.530	0.947	0.924
min Fz (N)	Pearson Correlation	-0.737	-0.737	-0.807	1.000	-0.695	0.502	-0.533	-0.712	-0.745
maxFz (N)	Pearson Correlation	0.741	0.741	0.747	-0.695	1.000	-0.542	0.456	0.827	0.877
min Fx (N)	Pearson Correlation	-0.595	-0.595	-0.656	0.502	-0.542	1.000	-0.322	-0.685	-0.639
maxFx (N)	Pearson Correlation	0.503	0.503	0.530	-0.533	0.456	-0.322	1.000	0.555	0.542
Peak power (W)	Pearson Correlation	0.902	0.902	0.947	-0.712	0.827	-0.685	0.555	1.000	0.968
Average power (W)	Pearson Correlation	0.868	0.868	0.924	-0.745	0.877	-0.639	0.542	0.968	1.000

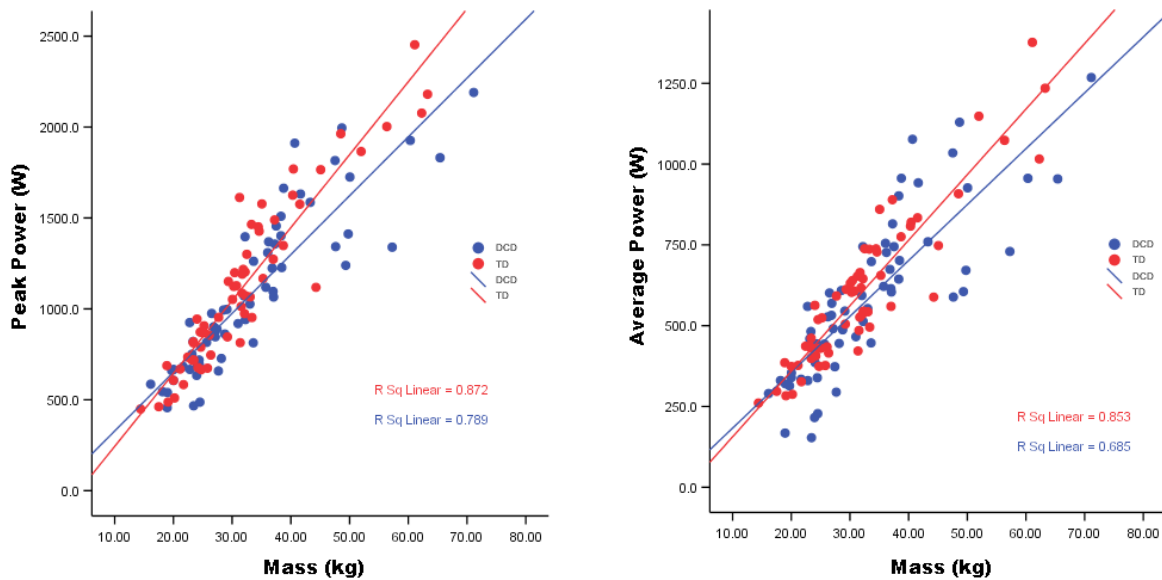


Figure A14: Relationship between mass and peak power (left panel) and, mass and average power (right panel).

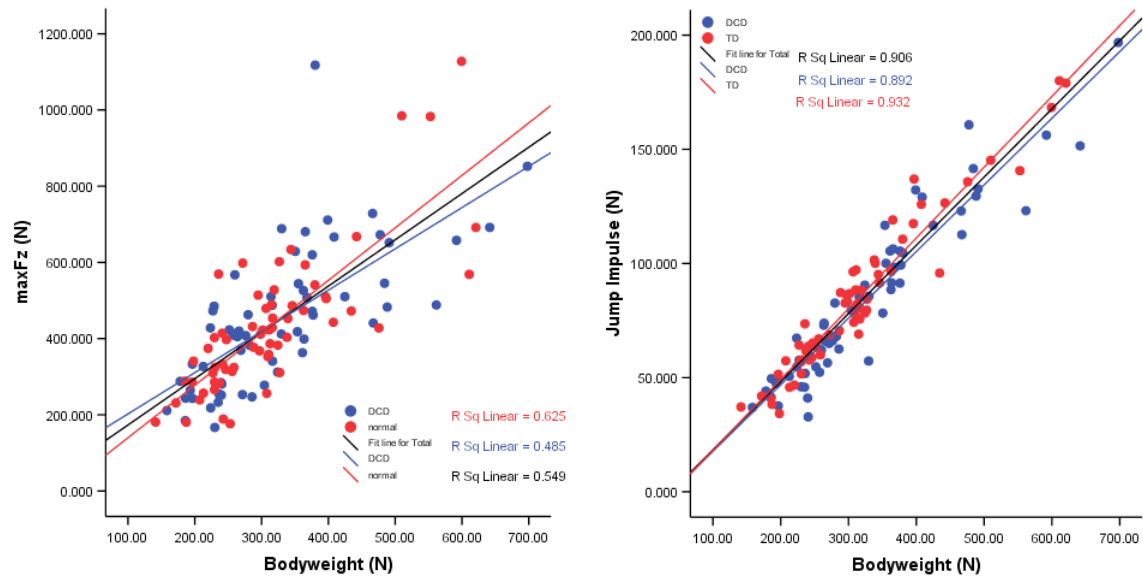


Figure A15: Relationship between bodyweight and peak vertical ground reaction force (left panel) and, bodyweight and jump impulse (right panel).

APPENDIX 14

Determining the Efficiency of Jumping

Loss in VCOM from the instant of peak VCOM and take-off was used to show the efficiency of the jumping movement. This difference between peak VCOM and VCOM_{take-off} was defined as VCOM_{drop-off} (shown in Equation A18). The VCOM_{drop-off} was expressed as a percentage of peak VCOM (Equation A19) to account for the differences in peak VCOM. It was assumed that the greater the loss (drop-off) in VCOM the less efficient the jumping movement. The descriptive statistics for all groups are presented in Table A7 below.

$$VCOM_{drop-off} = VCOM_{peak} - VCOM_{take-off} \quad \dots\dots\dots \text{Equation (A18)}$$

$$\text{Percentage drop-off in velocity (\%)} = \left(\frac{VCOM_{Drop-off}}{VCOM_{peak}} \right) \times 100 \quad \dots\dots\dots \text{Equation (A19)}$$

Table A7: Means and standard deviations (SD) for percentage drop-off across age-bands.

Group	Age-band	Drop off (%)*	
		Mean	SD
DCD	1	16	12
	2	12	2
	3	10	3
	4	10	3
	Total	12	7
TD	1	10	4
	2	12	6
	3	8	1
	4	8	2
	Total	10	5

* Indicates that for statistical analysis the data was transformed using natural log

† Indicates a significant main effect between groups

‡ Indicates a significant main effect between age-bands

The earlier occurrence of peak VCOM before take-off by the DCD group, resulted in a significantly ($F(1,116) = 8.142, p = 0.005, \eta^2 = 0.066$) greater loss or drop-off (12%) in VCOM at take-off. A 10 % drop-off was found in TD group making them 2% more efficient than the DCD group. Figure A16 shows consistent group differences at all age-bands with the exception of age-band 2 where the differences were small. In addition, the drop-off significantly decreased ($F(3,116) = 4.992, p = 0.003, \eta^2 = 0.114$) across age-bands, suggesting a more efficient jump (trend, $p = 0.001$).

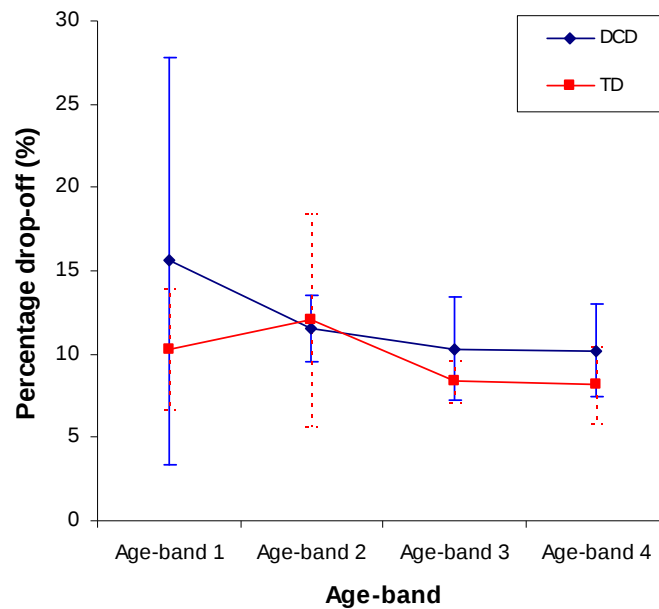


Figure A16: Mean drop-off (%) in peak vertical velocity of the centre of mass (peak VCOM) at take-off across age-bands.

Relationship between Jump height and VCOM at Take-off

A significant relationship between VCOM at take-off and jump height for all participants ($n = 124; r_{xy} = 0.685; p < 0.001; r_{xy}^2 = 0.471$) was found (Figure A17). In addition a significant relationship between the time elapsed from peak VCOM to take-off and jump

height for all participants ($n = 124$; $r_{xy} = -0.239$; $r_{xy}^2 = 0.057$; $p = 0.008$) was found, however the coefficient of determination (r_{xy}^2) was very low (6%).

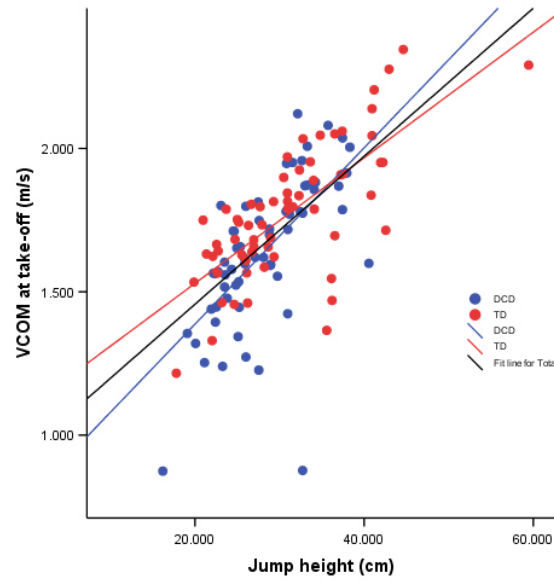


Figure A17: The relationship between vertical velocity of the centre of mass (VCOM) at take-off and jump height for the all participants.

APPENDIX 15

M-ABC Sub-scores

Cultural background and ethnicity of children can influence the total score achieved on the M-ABC (for a recent review see Mayson, Harris, & Bachman, 2007). For example, from one study, it was suggested that differences between cultures were present at the older age-bands (Miyahara et al., 1998). In Miyahara et al.'s study, Japanese children tended to be better in the dynamic balance section of the test whilst the American children favored the manual dexterity items. Conversely, from another study, Chinese children were found to be significantly better than American children on items related to manual dexterity and dynamic balance, while the American children performed better on ball skill items (Chow, Henderson, & Barnett, 2001). The purpose for the M-ABC assessment for this study was to characterise experimental groups from the total impairment scores. When the M-ABC scores were analysed at the sub-score level, differences between TD and DCD groups were not found at the older age-bands for ball skills (age-band 3 and 4), and to a lesser extent manual dexterity (age-band 4 only). Figure A18 shows the ball skills sub-score at each age-band. The lines of best fit for each gender show that males generally score better than girls for both groups. The DCD scores generally improve (toward zero) toward the older age-bands, where, scores are similar for the TD group. Lower ball skills sub-scores with older age-bands found in the DCD group, combined with one female participant from the TD group who scored 6, at age-band 4, were responsible for the lack of significant difference found between groups for this item. The manual dexterity sub-scores were more spread for the DCD group at age-bands 1, 2 and 3, however, at age-band 4 the number of DCD participants who scored more than the

TD group was noticeably less. Generally, the children were male (Figure A19), the female DCD age-band 4 all scored 2 or below, hence no significant difference at this age-band between groups. Generally, sub-scores were smaller at older age-bands for the DCD group; however, in contrast the balance sub-scores for both groups were larger (Figure A20). This may be related to increased body size or reflect the increased difficulty in the balance items across age-bands. Figure A20 shows the relationship between Body Mass Index (BMI) and balance sub-scores for TD ($r_{xy} = 0.077$, $r_{xy}^2 = 0.006$, $p = 0.552$) and DCD ($r_{xy} = 0.407$, $r_{xy}^2 = 0.166$, $p < 0.010$) groups. Body size as measured by BMI was related to balance sub-score for the DCD group only, yet it is unclear which is the cause or effect (e.g., Visser et al., 1998). That is, has the increase in BMI caused the impairment or was the child previously impaired and chose a sedentary lifestyle; it may be case that the group contains a combination of the two.

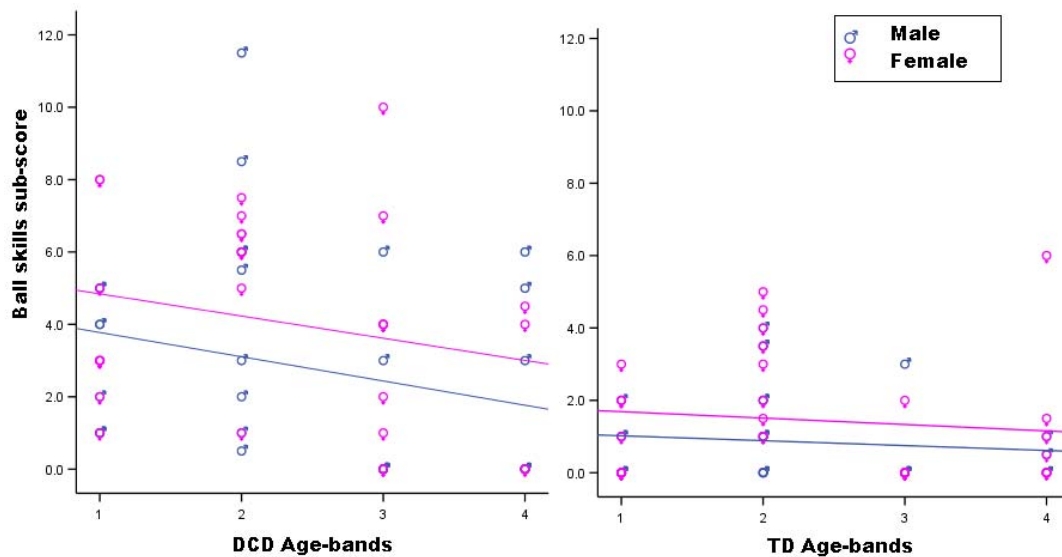


Figure A18: The gender distribution of ball skills sub-scores for both typically developing (TD) and Developmental Coordination Disorder (DCD). No significant difference was found at age-band 3 and 4.

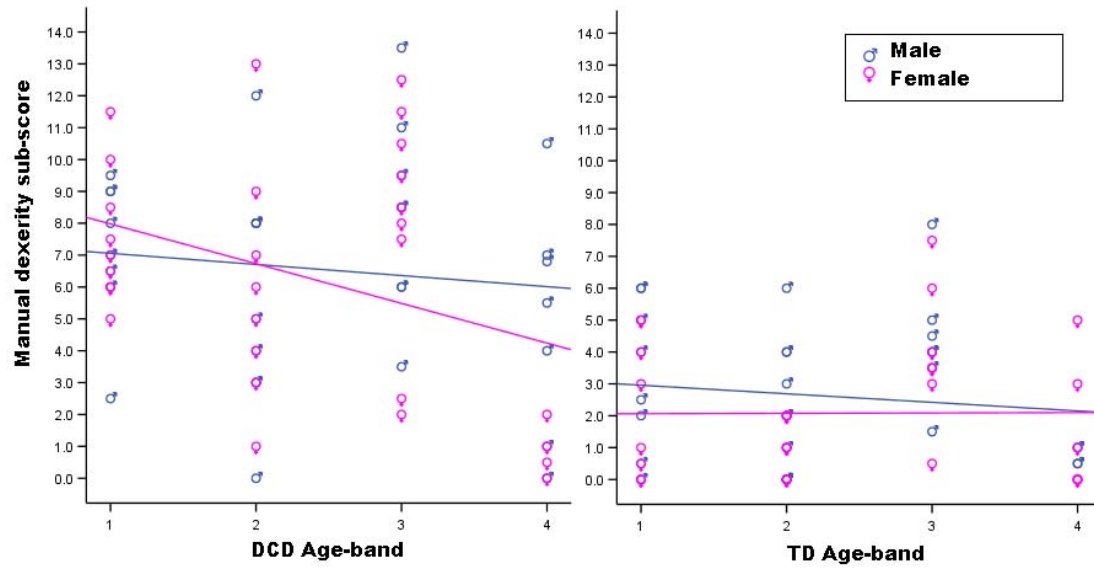


Figure A19: The gender distribution of manual dexterity sub-scores for both typically developing (TD) and Developmental Coordination Disorder (DCD). No significant difference was found at age-band 4.

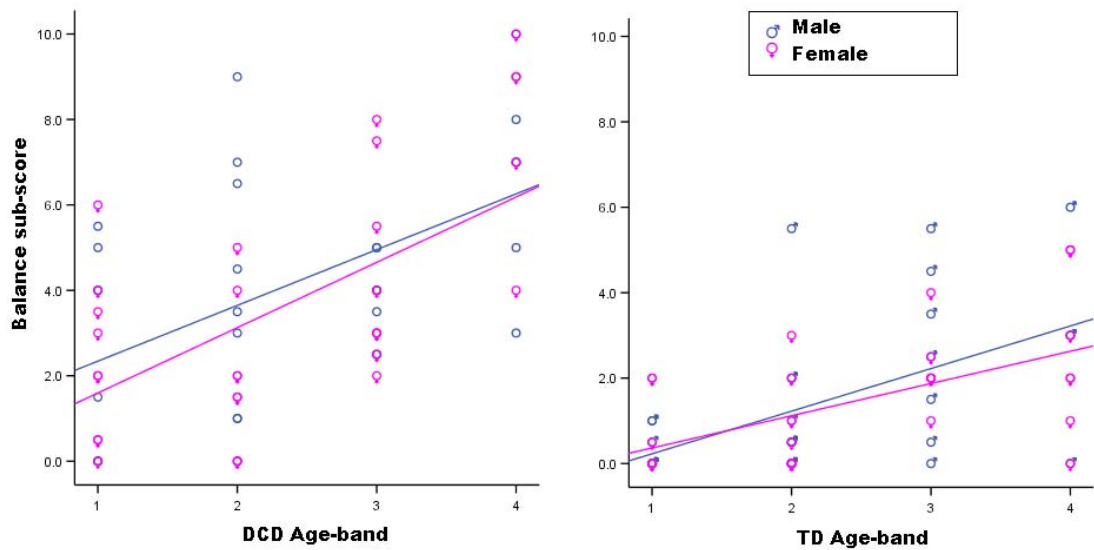


Figure A20: The gender distribution of balance sub-scores for both typically developing (TD) and Developmental Coordination Disorder (DCD).

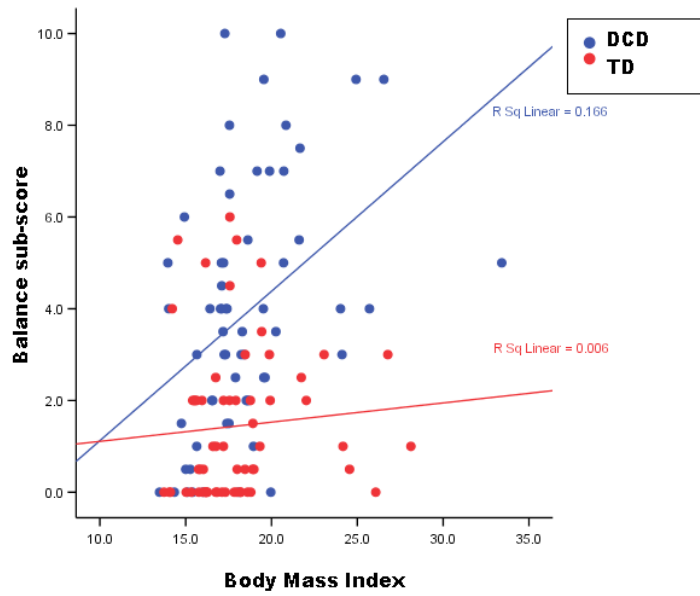


Figure A21: Body Mass Index (BMI) against Balance sub-score for both typically developing (TD) and Developmental Coordination Disorder (DCD).

APPENDIX 16

Warm-up

The choice of activities in preparation for an assessment of strength or explosive power is an important consideration. These pre-assessment activities are more commonly called warm-ups. Test reliability is further enhanced when sub-maximal practices are included as part of the warm-up (Young & Behm, 2003). Young and Behm (2003) did not recommend how many sub-maximal jumps were required, however, from another study that used untrained female subjects, three sub-maximal practice jumps prior to actual testing produced high levels of repeatability ($r_{xy} = 0.96$) for a vertical jump assessment (Goodwin et al., 1999). The authors proposed that three practice trials are sufficient to generate reliable vertical jump scores. This is consistent with the recommended guidelines from Harman et al. (1990) who suggested that three to five sub-maximal practice jumps were sufficient for untrained subjects to achieve 'peak jumping technique'.

The acute effect of stretching during the warm-up has been investigated (Knudson, Bennet, Corn, Leick & Smith, 2001; Fowles et al., 2000). The studies emphasised the negative impact of static stretching before jumping. Passive stretching of the plantar flexors was found to impair activation and contractile force during jumping. However, the importance of elevating body temperature during a warm-up appears to be advantageous in the performance of short-term "power" performance (Bergh, 1980). Enhanced jump performance has also been found following relatively heavy loaded squats prior to the jumping assessment (Baker, 1994; Baker 2001a; Baker 2001b; Gulich

& Schmidbleicher, 1996; Radcliffe & Radcliffe, 1996; Young, Jenner & Griffiths, 1998).

It should be noted that the benefit of such activities might be dependent upon the level and training age of the athletes. For participants who are not sufficiently conditioned, intensity may result in short-term fatigue resulting in a marked reduction in jump performance. In addition, no single conclusive explanation has been offered within the literature, although neural adaptations have been suggested. The proposed neural benefits of loaded squats include: increased descending activity from higher motor centres; direct myoelectrical potentiation; increased synchronization of motor unit firing; reduced peripheral inhibition from the Golgi tendon organ; reduced central inhibition from Renshaw cell; enhanced reciprocal inhibition of the antagonist musculature; or a favourable increase in the stiffness of the musculo-tendinous unit (Baker, 2003).

Squat (concentric only) and drop jump performance has been assessed following combinations of warm-up that included running, sub-maximal jumping and stretching (Young & Behm, 2003). It was found that jump performance and explosive force production was enhanced by including sub-maximal jumping in the warm-up. It was assumed that running would increase muscle temperature (although not measured) whilst the practice 'jumps opened up' specific neural pathways to facilitate motor unit activation thereby enhancing the readiness of the neuromuscular system. Furthermore, evidence for neural inhibition was found when stretching was employed however, no conclusive neural mechanism was proposed. It appears that for short-term explosive power performances such as maximal vertical jump attempts the pre-activities (warm-up) should involve activities such as running to raise muscle temperature and sub-maximal practices to 'open-up' the neural pathways.